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THERMAL ANALYSIS OF A CONCRETE INTEGRATED CASK

Report No 86-310-K

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ABSTRACT

A numerical study has been carried out to determine the maximum fuel sheath temperature within the cavity of a Concrete Integrated Cask (CIC) containing four rectangular modules for the dry storage of irradiated fuel. The analysis was based on the finite difference solution of the equations describing the three modes of heat transfer (conduction, convection and radiation). Results have been obtained in terms of temperature distributions throughout the cask and velocity plots within the fuel cavity for two decay heat levels and two ambient temperatures. For a decay heat level of 6 W/Bundle (10 year-cooled fuel) and an ambient temperature of 38°C the maximum fuel sheath temperature will be 96°C. Further work is recommended to verify the analysis results through temperature measurements on a prototype model.

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EXECUTIVE SUMMARY

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A two-dimensional heat transfer analysis of a Concrete Integrated Cask (CIC) for the dry storage of irradiated fuel has been performed to establish the maximum fuel sheath temperature within the fuel cavity and to assess the thermal behaviour of the cask in addressing safety related issues. The equations governing the heat flow throughout the cask were solved numerically using the finite difference method. The analysis provides the following results for two decay heat levels and two ambient temperatures.

1. Temperature distributions throughout the cask.

2. Velocity plots within the fuel cavity.

The results of this study indicate that the maximum fuel sheath temperature will be below the desired limit of 150°C. Further work is recommended in terms of temperature measurements on a prototype model to verify the theoretical predictions.

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LIST OF SYMBOLS

Subscripts

i,j,K	denotes conditions at a grid point
f	denotes fluid properties
e	denotes effective properties

Superscripts

n	denotes conditions at a time step

Variables

a	thermal diffusivity, m^2/s
c	specific heat, J/(Kg·°C)
g	acceleration of gravity, m/s^2
h_H	heat transfer coefficient for horizontal surface, W/(m °C)
h_V	heat transfer coefficient for vertical surface, W/(m °C)
K	flow conductivity, m
P	pressure, (KPa)a
q_S	outer surface heat flux, W/m
q_W	inner surface heat flux, W/m
Q_G	heat generation, W/m^3
Q_R	radiant heat exchange within fuel region, W/m^3
t	time, s
T	temperature field, °C
T_A	ambient temperature, °C

LIST OF SYMBOLS (Continued)

T_{AC}	average temperature of neighbouring finite difference cells, °C
T_{AFS}	average fuel surface temperature, °C
T_r	reference temperature, °C
T_S	outer concrete cask surface temperature, °C
T_W	inner concrete cask surface temperature, °C
x,y	coordinate system, m
u,v	velocity components, m/s

Greek Symbols

β	coefficient of volume expansion, 1/°C
ΔS	surface area of a finite difference cell for radiation, m^2
Δt	time step, s
ΔV	volume of a finite difference cell, m^3
ε_f	fuel emissivity
ε_E	outer surface emissivity
ε_I	inner surface emissivity
λ	thermal conductivity, W/(m·°C)
μ	absolute viscosity, Kg/(m·s)
ν	kinematic viscosity, m^2/s
ρ	density, Kg/m^3
σ	Stefan-Boltzmann constant, $W/(m^2 \cdot °K^4)$
Φ	porosity

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To Mr. H.N. Isaac
Manager, Nuclear Materials Management
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THERMAL ANALYSIS OF A CONCRETE INTEGRATED CASK

1.0 INTRODUCTION

The present study is a part of the Concrete Integrated Cask (CIC) development program within Ontario Hydro for the dry storage of 10 years cooled irradiated CANDU fuel.

The objectives of this investigation are:

i) To predict the temperature distribution throughout the cask.

ii) To estimate the maximum fuel sheath temperature using previous experimental results.

iii) To provide a basis for assessing the thermal behaviour of the fuel and to address safety related issues.

The CIC is a cylindrical structure (see Figure 1) with an inner cavity accommodating four rectangular fuel modules (see Figure 2). The total number of bundles that can be stored in the cask is 384. There are two carbon steel plates within the cavity to prevent the fuel bundles from falling off the module tubes. The wall of the cask is made of high density concrete which is covered inside and outside with 5 mm carbon steel liner. During interim storage the CIC will be stored outdoors at the Nuclear Site.

The report describes the theoretical treatment of the problem and the method of solution. The analysis results and the main conclusions of the study are presented and specific recommendations are made for future work.

2.0 ANALYSIS

2.1 Assumptions

In solving the equations governing the heat flow throughout the cask wall and cask cavity the following standard assumptions have been made.

Cask Wall

i) Thermal properties of the concrete wall are independent of temperature for the temperature range encountered.

ii) The heat loss from the cask outer surface is by natural convection and radiation.

iii) Thermal radiation emitted from the cask outer surface is absorbed by the surroundings.

Cask Cavity

i) Flow is incompressible and laminar.

ii) Fluid properties, with the exception of density, are independent of temperature.

iii) Flow through the fuel region obeys Darcy's law.

iv) Viscous dissipation is negligible.

2.2 Governing Equations

Based on the above assumptions the governing equations in two dimensions take the following form:

Cask Wall

$$\rho c \frac{\partial T}{\partial t} = \lambda \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) \qquad (2\text{-}1)$$

Cask Cavity

i) Fluid Region

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = o \qquad (2\text{-}2)$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{1}{\rho}\frac{\partial P}{\partial x} + g\beta\,(T-T_r) + \nu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) \quad (2\text{-}3)$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -\frac{1}{\rho}\frac{\partial P}{\partial x} + g\beta\,(T-T_r) + \nu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) \quad (2\text{-}4)$$

$$\rho c\left(\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y}\right) = \lambda\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) \quad (2\text{-}5)$$

i) Fuel Region

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = o \quad (2\text{-}6)$$

$$\frac{\rho}{\phi}\left(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right) = -\frac{\partial P}{\partial x} - \frac{\mu}{K}u + \rho g\beta\,(T-T_r) \quad (2\text{-}7)$$

$$\frac{\rho}{\phi}\left(\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y}\right) = -\frac{\partial P}{\partial x} - \frac{\mu}{K}v + \rho g\beta\,(T-T_r) \quad (2\text{-}8)$$

$$(\rho c)_e\frac{\partial T}{\partial t} + (\rho c)_f\, u\frac{\partial T}{\partial x} + (\rho c)_f\, v\frac{\partial T}{\partial y} = \lambda_e\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) + \dot{Q}_G - \dot{Q}_R \quad (2\text{-}9)$$

where:

$$Q_R = \sigma\varepsilon_F\frac{\Delta S}{\Delta V}\left(T^4 - T^4_{AC}\right) \quad (2.10)$$

2.3 Initial and Boundary Conditions

The above equations were solved numerically using the finite difference method subject to the following initial and boundary conditions:

Initial Conditions

at t = o: u=v=o; P=1; $T=T_A$ (2.11)

Boundary Conditions

i) Cask Outer Surface

This boundary condition includes the heat loss by natural convection and radiation.

$$q_s = \begin{cases} h_H(T_A - T_S) + \sigma\varepsilon_E(T_A^4 - T_S^4) & \text{for top surface} \\ h_V(T_A - T_S) + \sigma\varepsilon_E(T_A^4 - T_S^4) & \text{for vertical surface} \\ o & \text{for bottom surface} \end{cases} \quad (2\text{-}12)$$

where: h_H and h_V are evaluated from correlations of natural convection/1/.

ii) Cask Inner Surface

$$u_w = v_w = 0 \quad (2\text{-}13)$$

$$\dot{q}_w = \lambda_f \frac{\partial T}{\partial n} + \sigma\varepsilon_I \left(T_{AFS}^4 - T_w^4\right) \quad (2\text{-}14)$$

where:

$\frac{\partial T}{\partial n}$ = temperature gradient normal to the surface.

2.4 Method of Solution

As can be seen from Figures 1 and 2 the cask is of cylindrical geometry while the modules are rectangular. this makes the numerical modelling quite difficult since the existing computer code is based on the finite difference method. Therefore, certain simplifications have been made to the geometry. Figure 3 shows the two-dimensional region that has been analyzed by the finite difference method.

Details of the finite difference approximations to equation (2-1) for a nonuniform mesh can be found in Appendix A. The finite difference approximations for the fluid and fuel region equations are described elsewhere/1/.

3.0 RESULTS

The thermal analysis of a four-module concrete cask was performed using the computer code CIC. A listing of the program is given in Appendix B. The data used as input to the program were taken from Figure 1 and Tables 1 and 2. Four cases were analyzed for the conditions shown in Table 3.

The steady state results of the analysis for case 1 (Decay Heat= 6W/Bundle; Ambient Temperature=38°C) are shown in Figures 4 and 5. Figure 4 shows the temperature distribution across the cask wall and Figure 5 shows the velocity plot and temperature distribution within the cask cavity. As can be seen from these figures the maximum cask wall temperature occurs at the centre of the bottom inner surface and the maximum fuel temperature occurs closer to the bottom of the cask. This is due to the fact that the heat loss to the ground is assumed to be zero. Taking the maximum fuel temperature as the average temperature of the hottest module tube and using previous experimental results (see Figure 6), the maximum fuel sheath temperature is estimated from the following equation/1/.

$$(T_F)_{EST} = (T_T)_{ANAL} + (T_F - T_T)_{EXP} \qquad (3\text{-}1)$$

where:

T_F = maximum fuel sheath temperature

T_T = average module tube temperature

Thus the maximum fuel sheath temperature for case 1 is:

T_F = 94°C (from Figure 5) + 2°C (from Figure 6) = 96°C.

Similar results for the remaining 3 cases are shown in Figures 7 through 12 along with the corresponding maximum fuel sheath temperature.

4.0 CONCLUSIONS/RECOMMENDATIONS

i) For a 10 year-cooled fuel (decay heat = 6W/Bundle) and an ambient temperature of 38°C the maximum fuel sheath temperature is estimated to be 96°C.

ii) The effect of lowering the ambient temperature by 58°C (from 38°C to -20°C) has the effect of lowering the maximum fuel temperature by 51°C (compare Figures 5 and 8) for a decay heat level of 6W/Bundle.

iii) Increasing the decay heat from 6 to 12 W/Bundle raises the maximum fuel temperature by 91°C above the ambient temperature compared to a 56°C increase for the 6W/Bundle case. This indicates that the relationship between fuel temperature and decay heat level is not linear but exponential as one would expect.

iv) Full scale temperature measurements on a prototype model or small scale studies should be conducted to verify the theoretical predictions.

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REFERENCES

1. Taralis, D., "Thermal Analysis for the Design of an Irradiated Fuel Transportation Cask Under Normal Operating Conditions", Ontario Hydro Research Division Report No 83-221-K, May 1983.

2. Taralis, D., "Thermal Testing of Irradiated Fuel Storage Module Tubes in Water and Air", Ontario Hydro Research Division Report No 80-254-K, July 1980.

3. Mukherjee, P.K., "Concrete Integrated Cask Program, Thermal Properties of High Density Concrete", Ontario Hydro Research Division Report No 85-234-H, 1985.

APPENDIX A

FINITE DIFFERENCE APPROXIMATIONS OF HEAT CONDUCTION EQUATION

This Appendix presents the derivation of the finite difference approximations to the transient heat conduction equation (see equation A-1) for the determination of the temperature distribution throughout the cask wall.

$$\rho c \frac{\partial T}{\partial t} = \lambda \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) \qquad \text{(A-1)}$$

The finite difference equations have been obtained for a non-uniform mesh using the heat balance approach. The cask wall has been divided into finite cells. The cell structure is shown in Figure 13. To facilitate the application of the boundary conditions the cell has been further divided into four sub-cells. Writing the heat balance equation for sub-cell 1 the following equation is obtained:

$$\frac{\Delta t}{\Delta x_i} \lambda y_j TIP + \frac{\Delta t}{\Delta y_j} \lambda x_i TJP + \dot{q}_1 y_j + \dot{q}_3 x_i = \rho c x_i y_j \left(T_{i,j}^{n+1} - T_{i,j}^{n} \right) \qquad \text{(A-2)}$$

where:

$$TIP = T_{i+i,j}^{n} - T_{i,j}^{n}$$

$$TJP = T_{i,j+1}^{n} - T_{i,j}^{n}$$

Similar equations can be written for the remaining three sub-cells. Now the heat balance equation for a complete cell will be the sum of the heat balance equations of all sub-cells. Thus for an interior node the temperature at the next time step is given by:

$$T_{i,j}^{n+1} = T_{i,j}^{n} + (HL1 + HL2 + HL3 + HL4)/THC \qquad \text{(A-3)}$$

where:

HL1 to HL4 = left sides of heat balance equations of all sub-cells.

THC = heat capacity of a complete cell.

APPENDIX B

COMPUTER CODE CIC

A listing of the computer program CIC used for the thermal analysis of an Integrated Concrete Cask is presented in this Appendix. It consists of a main program and 24 subroutines.

```
      COMMON /BL1/ DX,DY,DZ,DXFA,DYFA,DZFA
      COMMON /BL2/ R,B,VK,THD,CP
      COMMON /BL3/ CR,ETD
      COMMON /BL4/ DT
      COMMON /BL5/ T1,T2,T3,T4
      COMMON /BL6/ M,N,L
      COMMON /BL7/ MM1,NM1,LM1,MM2,NM2,LM2
      COMMON /BL8/ TR,G
      COMMON /BL9/ ND
      COMMON /BL10/ I,J,K
      COMMON /BL11/ A11,A12,A13,X33,XM323,XP323
      COMMON /BL12/ A11M,A12M,A13M,X33M,XM323M,XP323M
      COMMON /BL21/ B11,B12,B13,Y33,YM323,YP323
      COMMON /BL22/ B11N,B12N,B13N,Y33N,YM323N,YP323N
      COMMON /BL40/ FLSI,FLSE
      COMMON /BL51/ FKU,FKV,FKW
      COMMON /BL52/ SPD
      COMMON /BL53/ TDIA
      COMMON /BL54/ RD1,RD2,RD3,RD4
      COMMON /BL55/ CST1,CST2,CST3,CST4
      COMMON /BL56/ EX2,EX3,EX4
      COMMON /BL57/ UC,VC,WC
      COMMON /BL58/ IS,IE,JS,JE,KS,KE
      COMMON /BL59/ TOL,CRT,ITM,NGP,ITER
      COMMON /BL60/ IFU,IFV,IFW,IFT
      COMMON /BL61/ EPR
      COMMON /BL71/ IDXS,JDYS
      COMMON /BL72/ DXP,DYP
      COMMON /BL83/ SIG,TABS
      COMMON /BL84/ EB,EM
      COMMON /BL85/ M1,M2,N1,N2
      COMMON /BL86/ TWR1,TWR3,TWR4
      COMMON /BL87/ TFR1,TFR3,TFR4
      COMMON /BL88/ ES,EW
      COMMON /BLS/ S1,S2,S3,S4
      COMMON /CND2/ TC1,TC2,TC3,TC4
      COMMON /CND3/ TA,HTP,HBP,HLP
      COMMON /CND4/ TF1,TF2,TF3,TF4
      COMMON /CND5/ IRF,ICF
      COMMON /CND7/ DXC,DYC
      DIMENSION A(4,10,14,1)
      DIMENSION U(10,14,1),V(10,14,1),W(10,14,1),P(10,14,1),T(10,14,1)
      DIMENSION Q(10,14,1),NCP(10,14,1),DFDP(10,14,1)
      DIMENSION UP(10,14),VP(10,14),TP(10,14)
      DIMENSION C(2,14,23)
      DIMENSION QR(10,14,1)
      DIMENSION NCR(10,14,1),NCC(14,23),NFL(14,23)
      DIMENSION DX(25),DY(25),DZ(25),DXFA(25),DYFA(25),DZFA(25)
      DIMENSION X(25),Y(25),Z(25)
      DIMENSION DFDP1(25),DFDP2(25),DFDP3(25)
      DIMENSION DXP(25),DYP(25)
      DIMENSION DXC(25),DYC(25)
      DIMENSION T1(25),T2(25),T3(25),T4(25)
      DIMENSION TF1(25),TF2(25),TF3(25),TF4(25)
C
C     DATA FOR RADIATION
C
      DATA IRF/1/
      DATA ES,EW/0.5,0.7/
      DATA EB,EM/2*0.7/
      DATA SIG,TABS/5.669E-8,273.0/
C
C     DATA FOR CONVECTIVE HEAT TRANSFER
C
      DATA DT/0.1/
      DATA ND/2/
```

```
      DATA EPR/0.51/
      DATA NS,NTS/9999,1/
      DATA NCOUNT,NW/0,1/
      DATA ITM/100/
      DATA TOL/1.0E-4/
      DATA SPD/1.7/
      DATA G/9.81/
      DATA TDIA/0.1/
      DATA UC,VC,WC/3*0.0/
      DATA NPF,NPM/1,2/
      DATA DX/3*0.0875,7*0.1075,15*0.0/
      DATA DY/11*0.24,3*0.12,11*0.0/
      DATA M,N,L/10,14,1/
      DATA M1,M2,N1,N2/4,9,2,11/
      DATA R,CP,TK,VK,B/0.96,1009.0,0.03,2.22E-5,2.736E-3/
      DATA RS,CPS,TKS/0.96,1009.0,0.03/
      DATA TR/253.0/
      DATA CST1,CST2,CST3,CST4/9.0E-4,1.3022E-3,8.5467E-3,34.93E-3/
      DATA EX2,EX3,EX4/0.1605,0.62,0.8858/
      DATA RD1,RD2,RD3,RD4/1.0E1,6.0E1,2.0E2,1.0E4/
      DATA IDXS,JDYS/2,7/
      DATA SCFX,SCFY/2*1.0/
      DATA QU/751.68/
      DATA IBC/1/
      DATA NRED/0/
      DATA ICAV/1/
C
C     DATA FOR CONDUCTION
C
      DATA MC,NC/14,23/
      DATA IA,JA,JB/6,6,18/
      DATA DXC/5*0.096,2*0.0875,6*0.1075,12*0.0/
      DATA DYC/5*0.096,10*0.24,2*0.12,5*0.096,3*0.0/
      DATA TKC,RC,CPC/2.77,3500.0,838.0/
      DATA TKF/0.03/
      DATA DTC/100.0/
      DATA NSC,NTC/9999,50000/
      DATA ICF/1/
      DATA IWAL/1/
      DATA TA,TWI/253.0,318.0/
      DATA STP,SBP,SLP/2*2.6,3.6/
C
      OPEN(5,FILE='IN2.DAT',STATUS='OLD')
      OPEN(6,FILE='OUT2.DAT',STATUS='NEW')
      OPEN(9,FILE='SAV2.DAT',STATUS='NEW')
C
C     EVALUATION OF CONSTANTS FOR CONDUCTION
C
      MM1=M-1
      NM1=N-1
      NP1=N+1
      MM2=M-2
      NM2=N-2
      LM1=0
      LM2=0
      TC=(RC*CPC)/(2.0*DTC)
      TC1=TC
      TC2=2.0*TC
      TC3=3.0*TC
      TC4=4.0*TC
      DO 91 J=1,NC
      DO 91 I=1,MC
      C(1,I,J)=TWI
   91 CONTINUE
C
C     EVALUATION OF CONSTANTS FOR CONVECTION
```

```
C
      K=1
      Z(K)=0.0
      DFDP3(K)=0.0
      THD=TK/(R*CP)
      CF=R*CP
      CS=RS*CPS
      ETK=EPR*TK+(1.0-EPR)*TKS
      EHC=EPR*CF+(1.0-EPR)*CS
      ETD=ETK/EHC
      CR=CF/EHC
      XL=0.0
      YL=0.0
      DO 1 I=2,MM1
      DXP(I)=DX(I)/SCFX
      XL=XL+DXP(I)
    1 CONTINUE
      DO 2 J=2,MM1
      DYP(J)=DY(J)/SCFY
      YL=YL+DYP(J)
    2 CONTINUE
      DO 4 I=2,MM1
      DXFA(I-1)=(DX(I-1)+DX(I))/2.0
      DXFA(I)=(DX(I)+DX(I+1))/2.0
      IF(I.EQ.2) X(I-1)=-DX(I-1)/2.0
      X(I)=X(I-1)+DXFA(I-1)
      DFDP1(I)=(1.0/DXFA(I-1)+1.0/DXFA(I))/DX(I)
    4 CONTINUE
      DO 6 J=2,MM1
      DYFA(J-1)=(DY(J-1)+DY(J))/2.0
      DYFA(J)=(DY(J)+DY(J+1))/2.0
      IF(J.EQ.2) Y(J-1)=-DY(J-1)/2.0
      Y(J)=Y(J-1)+DYFA(J-1)
      DFDP2(J)=(1.0/DYFA(J-1)+1.0/DYFA(J))/DY(J)
    6 CONTINUE
      NGP=MM2*NM2
      PRL=VK/THD
      GRF=0.0
      RAH=GRF*PRL
      IF(IBC.EQ.1) CALL TCL
      IF(IBC.EQ.2) CALL TCQ
C
C     INITIALIZATION OF VARIABLES
C
      DO 10 J=1,N
      DO 10 I=1,M
      U(I,J,K)=0.0
      V(I,J,K)=0.0
      W(I,J,K)=0.0
      T(I,J,K)=TWI
      P(I,J,K)=1.0
      QR(I,J,K)=0.0
      Q(I,J,K)=0.0
      NCP(I,J,K)=NPF
   10 CONTINUE
      DO 15 J=N1,N2
      DO 15 I=M1,M2
      NCP(I,J,K)=NPM
      Q(I,J,K)=QU/EHC
   15 CONTINUE
      DO 42 J=1,N
      JT=NP1-J
      WRITE(6,41) (NCP(I,JT,K),I=1,M)
   41 FORMAT(25I5)
   42 CONTINUE
      WRITE(6,115)
```

```
      CALL NRAD(NCR)
      TIMC=0.0
      TIME=0.0
      IF(NRED.GT.0) CALL READ(TIMC,TIME,C,U,V,W,T,P,MC,NC)
      DO 45 J=1,N
      DO 45 I=1,M
      A(4,I,J,K)=T(I,J,K)
   45 CONTINUE
C
C     INCREMENT OF TIME
C
      IF(IWAL.EQ.0) GO TO 400
C
C     SOLUTION OF HEAT CONDUCTION
C
      CALL NDS(NCC,NFL,MC,NC,IA,JA,JB)
      NCNT=0
      NWC=1
   32 CONTINUE
      TIMC=TIMC+DTC
      TSSM=0.0
      DO 102 JSM=1,NC
      TSSM=TSSM+C(1,1,JSM)
  102 CONTINUE
      DO 104 ISM=2,MC
      TSSM=TSSM+C(1,ISM,NC)
  104 CONTINUE
      TSG=TSSM/FLOAT(NC+MC-1)
      CALL CVR(TA,TSG,STP,SBP,SLP,HTP,HBP,HLP)
      CALL FLT(A,IA,JA,JB,MC,NC)
      IF(IRF.GT.0) CALL TAVF(A)
      CALL CNS(TKC,TKF,MC,NC,C,NCC,NFL)
      NCNT=NCNT+1
      IF(NCNT.NE.NWC) GO TO 120
      NWC=NWC+NSC
      IF(NCNT.EQ.1) NSC=NSC+1
      WRITE(6,172)
  172 FORMAT('1')
      WRITE(6,112) TIMC
  112 FORMAT(' TIME=',E15.5)
      WRITE(6,115)
  115 FORMAT(/)
      DO 118 J=1,NC
      JT=NC+1-J
      IW=MC
      IF(J.GT.JA.AND.J.LT.JB) IW=IA
      WRITE(6,116) ((C(2,I,JT)-273.0),I=1,IW)
  116 FORMAT(14F9.2)
  118 CONTINUE
      WRITE(6,92) HTP,HBP,HLP
   92 FORMAT(' HTP=',E12.5,2X,'HBP=',E12.5,2X,'HLP=',E12.5)
      CALL AST(C,IA,MC,JA,JB,NC)
  120 CONTINUE
  400 CONTINUE
      IF(ICAV.EQ.0) GO TO 500
   11 CONTINUE
      TIME=TIME+DT
C
C     CALCULATION OF VELOCITY FIELD
C
      DO 5 J=2,NM1
      DO 5 I=2,MM1
      CALL PMS(U,V,W)
      IFU=NCP(I,J,K)
      IFV=NCP(I,J,K)
      IFW=NCP(I,J,K)
```

```
      IF(I.LT.MM1) CALL US(A,U,V,W,P)
      IF(J.LT.NM1) CALL VS(A,U,V,W,P,T)
    5 CONTINUE
      CALL VBC(A)
C
C     CALCULATION OF PRESSURE FIELD
C
      DO 8 I=2,MM1
      DO 8 J=2,NM1
      DFDP(I,J,K)=DT*(DFDP1(I)+DFDP2(J)+DFDP3(K))
    8 CONTINUE
      CALL PS(A,P,DFDP)
      CALL VBC(A)
C
C     CALCULATION OF TEMPERATURE FIELD
C
      IF(IRF.GT.0) CALL TAVW(C,IA,JA,JB,MC,NC)
      IF(IRF.GT.0) CALL RAD(NCR,T,QR,EHC)
      DO 35 J=2,NM1
      DO 35 I=2,MM1
      IFT=NCP(I,J,K)
      CALL TS(A,U,V,W,T,Q,QR)
   35 CONTINUE
      CALL ET(C,IA,JA,JB,MC,NC)
      IF(IBC.EQ.1) CALL TBC1(A)
      IF(IBC.EQ.2) CALL TBC2(A)
C
C     UPDATING OF VARIABLES
C
      DO 50 J=1,N
      DO 50 I=1,M
      U(I,J,K)=A(1,I,J,K)
      V(I,J,K)=A(2,I,J,K)
      T(I,J,K)=A(4,I,J,K)
   50 CONTINUE
C
C     OUTPUT OF RESULTS
C
  500 CONTINUE
      TBFS=0.0
      NCOUNT=NCOUNT+1
      IF(NCOUNT.NE.NW) GO TO 60
      NW=NW+NS
      IF(NCOUNT.EQ.1) NS=NS+1
      WRITE(6,72)
   72 FORMAT('1')
      WRITE(6,12) TIME
   12 FORMAT(' TIME=',E15.7)
      WRITE(6,71) NCOUNT,ITER,TOL,CRT
   71 FORMAT(' NCOUNT=',I10,' ITER=',I10,' TOL=',E15.5,' CRT=',E15.5)
      WRITE(6,56) GRF,PRL,RAH
   56 FORMAT(' GRF=',E15.5,' PRL=',E15.5,' RAH=',E15.5)
      WRITE(6,51)
   51 FORMAT(/)
      WRITE(6,52) Z(K)
   52 FORMAT(' RESULTS AT PLANE Z=',E15.4,' ')
      JM=0
      DO 55 J=2,NM1
      JM=JM+1
      WRITE(6,53) Y(J)
   53 FORMAT(' Y=',E15.4)
      IM=0
      DO 55 I=2,MM1
      IM=IM+1
      IF(ND.GE.1) UAV=0.5*(A(1,I,J,K)+A(1,I-1,J,K))
      IF(ND.GE.2) VAV=0.5*(A(2,I,J,K)+A(2,I,J-1,K))
```

```
      IF(ND.GE.3) WAV=0.5*(A(3,I,J,K)+A(3,I,J,K-1))
      UP(IM,JM)=UAV
      VP(IM,JM)=VAV
      TP(IM,JM)=A(4,I,J,K)
      WRITE(6,54)
     'I,J,K,X(I),UAV,VAV,WAV,(A(4,I,J,K)-273.0),P(I,J,K)
     ',Q(I,J,K),QR(I,J,K)
   54 FORMAT(3I5,8E14.5)
      TBFS=TBFS+(A(4,I,J,K)-273.0)
   55 CONTINUE
      TBF=TBFS/NGP
      WRITE(6,58) TBF
   58 FORMAT(' TBF=',E15.5)
   60 CONTINUE
C     IF(NCOUNT.EQ.NTS) CALL WRITE(TIMC,TIME,C,U,V,W,T,P,MC,NC)
      IF(NCNT.EQ.NTC) CALL WRITE(TIMC,TIME,C,U,V,W,T,P,MC,NC)
      IF(NCOUNT.LT.NTS) GO TO 11
      IF(NCNT.LT.NTC) GO TO 32
      STOP
      END
```

```
      SUBROUTINE TCL
      COMMON /BL1/ DX,DY,DZ,DXFA,DYFA,DZFA
      COMMON /BL6/ M,N,L
      COMMON /BL7/ MM1,NM1,LM1,MM2,NM2,LM2
      COMMON /BLS/ S1,S2,S3,S4
      DIMENSION DX(25),DY(25),DZ(25),DXFA(25),DYFA(25),DZFA(25)
      S1=DX(1)/DX(2)
      S2=DX(M)/DX(MM1)
      S3=DY(1)/DY(2)
      S4=DY(N)/DY(NM1)
      RETURN
      END
```

```
      SUBROUTINE TCQ
      COMMON /BL1/ DX,DY,DZ,DXFA,DYFA,DZFA
      COMMON /BL6/ M,N,L
      COMMON /BL7/ MM1,NM1,LM1,MM2,NM2,LM2
      COMMON /BL11/ A11,A12,A13,X33,XM323,XP323
      COMMON /BL12/ A11M,A12M,A13M,X33M,XM323M,XP323M
      COMMON /BL21/ B11,B12,B13,Y33,YM323,YP323
      COMMON /BL22/ B11N,B12N,B13N,Y33N,YM323N,YP323N
      DIMENSION DX(25),DY(25),DZ(25),DXFA(25),DYFA(25),DZFA(25)
      X1=DX(1)/2.0
      X2=DXFA(1)
      X3=DXFA(2)+X2
      X11=X1**2
      X33=X3**2
      XM23=X2-X3
      XM123=X1/XM23
      XM323=X3/XM23
      XP23=X2+X3
      XP323=X3*XP23
      XP123=X1*XP23
      A1=X11-XP123-X33+XP323
      A11=1.0/A1
      A12=XM123/A1
      A13=XM323/A1
      X1M=DX(M)/2.0
      X2M=DXFA(M-1)
      X3M=DXFA(M-2)+X2M
      X11M=X1M**2
      X33M=X3M**2
      XM23M=X2M-X3M
      XM123M=X1M/XM23M
      XM323M=X3M/XM23M
      XP23M=X2M+X3M
      XP323M=X3M*XP23M
      XP123M=X1M*XP23M
      A1M=X11M-XP123M-X33M+XP323M
      A11M=1.0/A1M
      A12M=XM123M/A1M
      A13M=XM323M/A1M
      Y1=DY(1)/2.0
      Y2=DYFA(1)
      Y3=DYFA(2)+Y2.
      Y11=Y1**2
      Y33=Y3**2
      YM23=Y2-Y3
      YM123=Y1/YM23
      YM323=Y3/YM23
      YP23=Y2+Y3
      YP323=Y3*YP23
      YP123=Y1*YP23
      B1=Y11-YP123-Y33+YP323
      B11=1.0/B1
      B12=YM123/B1
      B13=YM323/B1
      Y1N=DY(N)/2.0
      Y2N=DYFA(N-1)
      Y3N=DYFA(N-2)+Y2N
      Y11N=Y1N**2
      Y33N=Y3N**2
      YM23N=Y2N-Y3N
      YM123N=Y1N/YM23N
      YM323N=Y3N/YM23N
      YP23N=Y2N+Y3N
      YP323N=Y3N*YP23N
      YP123N=Y1N*YP23N
      B1N=Y11N-YP123N-Y33N+YP323N
```

```
B11N=1.0/B1N
B12N=YM123N/B1N
B13N=YM323N/B1N
RETURN
END
```

```
      SUBROUTINE NRAD(NCR)
      COMMON /BL6/ M,N,L
      COMMON /BL85/ M1,M2,N1,N2
      DIMENSION NCR(M,N,L)
      M1P=M1+1
      M2M=M2-1
      N1P=N1+1
      N2M=N2-1
      DO 10 J=N1,N2
      DO 10 I=M1,M2
      NCR(I,J,1)=5
   10 CONTINUE
      NCR(M1,N1,1)=1
      NCR(M1,N2,1)=3
      NCR(M2,N1,1)=7
      NCR(M2,N2,1)=9
      DO 15 J=N1P,N2M
      NCR(M1,J,1)=2
      NCR(M2,J,1)=8
   15 CONTINUE
      DO 20 I=M1P,M2M
      NCR(I,N1,1)=4
      NCR(I,N2,1)=6
   20 CONTINUE
      DO 25 J=N1,N2
      JT=N2-J+N1
      WRITE(6,22) (NCR(I,JT,1),I=M1,M2)
   22 FORMAT(25I3)
   25 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE READ(TIMC,TIME,C,U,V,W,T,P,MC,NC)
      COMMON /BL6/ M,N,L
      DIMENSION C(2,MC,NC)
      DIMENSION U(M,N,L),V(M,N,L),W(M,N,L),T(M,N,L)
      DIMENSION P(M,N,L)
      READ(5,30) TIMC
      DO 10 J=1,NC
      DO 10 I=1,MC
      READ(5,30) C(1,I,J)
   10 CONTINUE
      READ(5,30) TIME
      DO 20 K=1,L
      DO 20 J=1,N
      DO 20 I=1,M
      READ(5,40)
     !U(I,J,K),V(I,J,K),W(I,J,K),T(I,J,K),P(I,J,K)
   20 CONTINUE
   30 FORMAT(E14.5)
   40 FORMAT(5E14.5)
      RETURN
      END
```

```
      SUBROUTINE NDS(NCC,NFL,MC,NC,IA,JA,JB)
      DIMENSION NCC(MC,NC),NFL(MC,NC)
      IAP=IA+1
      IAM=IA-1
      JAP=JA+1
      JAM=JA-1
      JBP=JB+1
      JBM=JB-1
      MCM=MC-1
      NCM=NC-1
      NCP=NC+1
      ISP=2
      JSP=2
C
C     NODAL CODES FOR CONDUCTION
C
      DO 10 J=1,NC
      DO 10 I=1,MC
      NCC(I,J)=17
   10 CONTINUE
      DO 15 J=JA,JB
      DO 15 I=IA,MC
      NCC(I,J)=18
   15 CONTINUE
      DO 20 I=IAP,MCM
      NCC(I,JA)=6
      NCC(I,JB)=2
   20 CONTINUE
      DO 25 J=JAP,JBM
      NCC(IA,J)=4
   25 CONTINUE
      DO 30 I=ISP,MCM
      NCC(I,1)=13
      NCC(I,NC)=9
   30 CONTINUE
      DO 35 J=JSP,NCM
      NCC(1,J)=11
   35 CONTINUE
      DO 40 J=JBP,NCM
      NCC(MC,J)=15
   40 CONTINUE
      DO 45 J=JSP,JAM
      NCC(MC,J)=16
   45 CONTINUE
      NCC(MC,JB)=1
      NCC(IA,JB)=3
      NCC(IA,JA)=5
      NCC(MC,JA)=7
      NCC(MC,NC)=8
      NCC(1,NC)=10
      NCC(1,1)=12
      NCC(MC,1)=14
C
C     NODAL CODES FOR CONVECTION
C
      DO 48 J=1,NC
      DO 48 I=1,MC
      NFL(I,J)=5
   48 CONTINUE
      DO 50 J=JA,JB
      NFL(IA,J)=1
      NFL(MC,J)=2
   50 CONTINUE
      DO 55 I=IAP,MC
      NFL(I,JA)=3
      NFL(I,JB)=4
```

```
55 CONTINUE
   WRITE(6,70)
   DO 60 J=1,NC
   JT=NCP-J
   WRITE(6,75) (NCC(I,JT),I=1,MC)
60 CONTINUE
   WRITE(6,70)
   DO 65 J=1,NC
   JT=NCP-J
   WRITE(6,75) (NFL(I,JT),I=1,MC)
65 CONTINUE
70 FORMAT(/)
75 FORMAT(25I3)
   RETURN
   END
```

```
      SUBROUTINE CVR(TA,TSG,STP,SBP,SLP,HTP,HBP,HLP)
      COMMON /PRTS/ RA,TKAB,VISS,VISH,BET,CPA,GRV
      FTA=1.8*TA+32.0
      FTSG=1.8*TSG+32.0
      FSTP=STP/0.3048
      FSBP=SBP/0.3048
      FSLP=SLP/0.3048
      CALL AIR(FTA,FTSG,TF,TSTA)
      CALL HTC(FSTP,FSBP,FSLP,TSTA,HTP,HBP,HLP)
      HTP=5.678*HTP
      HBP=5.678*HBP
      HLP=5.678*HLP
      RETURN
      END
```

```
      SUBROUTINE AIR(TA,TSG,TF,TSTA)
      COMMON /PRTS/ RA,TKAB,VISS,VISH,BET,CPA,GRV
      DATA CPA/0.24/
      DATA GRV/32.2/
      DATA RGA,PRS/53.35,14.7/
      DATA C0,C,C1,CF/0.632,245.0,-12.0,1.0E-5/
      DATA A0,A1,A2/4.0201,7.4582E-1,-5.7171E-4/
      DATA A3,A4/2.9928E-7,-6.2524E-11/
      TSTA=TSG-TA
      TF=(TSG+TA)/2.0
      TDR=TF+459.69
      TDK=(5.0/9.0)*TDR
      BET=1.0/TDR
      RA=(PRS*144.0)/(RGA*TDR)
      CT=C/TDK
      CT1=C1/TDK
      CTC=CT*(10.0**CT1)
      TKAC=(CF*C0*SQRT(TDK))/(1.0+CTC)
      TKAB=241.908*TKAC
      VISC=A0+A1*TDK+A2*TDK**2+A3*TDK**3+A4*TDK**4
      VISH=0.00024191*VISC
      VISS=VISH/3600.0
      RETURN
      END
```

```
      SUBROUTINE HTC(ST,SB,SL,TSTA,HT,HB,HL)
      COMMON /PRTS/ RA,TKAB,VISS,VISH,BET,CPA,GRV
      DATA RL1,RU1/1.0E5,2.0E7/
      DATA RL2,RU2/2.0E7,3.0E10/
      DATA RL3,RU3/3.0E5,3.0E10/
      DATA RL4,RU4/1.0E5,1.0E9/
      DATA RL5,RU5/1.0E9,1.0E12/
      GRF=(RA**2*GRV*BET*TSTA)/(VISS**2)
      GRL=GRF*SL**3
      GRB=GRF*SB**3
      GRT=GRF*ST**3
      PR=(CPA*VISH)/TKAB
      RYL=GRL*PR
      RYB=GRB*PR
      RYT=GRT*PR
      IF(TSTA.LE.0.0) GO TO 5
      IF(RYT.GE.RL1.AND.RYT.LE.RU1) HNUT=0.54*RYT**0.25
      IF(RYT.GT.RL2.AND.RYT.LE.RU2) HNUT=0.14*RYT**0.33333
      IF(RYB.GE.RL3.AND.RYB.LE.RU3) HNUB=0.27*RYB**0.25
      IF(GRL.LT.RL4) HNUL=0.48*GRL**0.25
      IF(RYL.GE.RL4.AND.RYL.LE.RU4) HNUL=0.555*RYL**0.25
      IF(RYL.GT.RL5.AND.RYL.LE.RU5) HNUL=0.021*RYL**0.4
      HT=(TKAB*HNUT)/ST
      HB=(TKAB*HNUB)/SB
      HL=(TKAB*HNUL)/SL
    5 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE FLT(A,IA,JA,JB,MC,NC)
      COMMON /BL6/ M,N,L
      COMMON /BL7/ MM1,NM1,LM1,MM2,NM2,LM2
      COMMON /CND4/ TF1,TF2,TF3,TF4
      DIMENSION A(4,M,N,L)
      DIMENSION TF1(25),TF2(25),TF3(25),TF4(25)
      K=1
      JM=JB-1
      JP=JA+1
      DO 10 J=JP,JM
      JJ=J-JA+1
      TF1(J)=(A(4,2,JJ,K)+A(4,2,JJ+1,K))/2.0
   10 CONTINUE
      TF1(JA)=A(4,2,2,K)
      TF1(JB)=A(4,2,NM1,K)
      IP=IA+1
      MCM=MC-1
      DO 20 I=IP,MCM
      II=I-IA+1
      TF3(I)=(A(4,II,2,K)+A(4,II+1,2,K))/2.0
      TF4(I)=(A(4,II,NM1,K)+A(4,II+1,NM1,K))/2.0
   20 CONTINUE
      TF3(MC)=A(4,MM1,2,K)
      TF4(MC)=A(4,MM1,NM1,K)
      RETURN
      END
```

```
      SUBROUTINE TAVF(A)
      COMMON /BL6/ M,N,L
      COMMON /BL7/ MM1,NM1,LM1,MM2,NM2,LM2
      COMMON /BL85/ M1,M2,N1,N2
      COMMON /BL87/ TFR1,TFR3,TFR4
      DIMENSION A(4,M,N,L)
      K=1
      ICNT=0
      SUMF1=0.0
      DO 10 J=N1,N2
      ICNT=ICNT+1
      SUMF1=SUMF1+A(4,M1,J,K)
   10 CONTINUE
      TFR1=SUMF1/FLOAT(ICNT)
      ICNT=0
      SUMF3=0.0
      SUMF4=0.0
      DO 20 I=M1,MM1
      ICNT=ICNT+1
      SUMF3=SUMF3+A(4,I,N1,K)
      SUMF4=SUMF4+A(4,I,N2,K)
   20 CONTINUE
      TFR3=SUMF3/FLOAT(ICNT)
      TFR4=SUMF4/FLOAT(ICNT)
      RETURN
      END
```

```
      SUBROUTINE CNS(TKC,TKF,MC,NC,C,NCC,NFL)
      COMMON /BL1/ DX,DY,DZ,DXFA,DYFA,DZFA
      COMMON /BL7/ MM1,NM1,LM1,MM2,NM2,LM2
      COMMON /BL83/ SIG,TABS
      COMMON /BL87/ TFR1,TFR3,TFR4
      COMMON /BL88/ ES,EW
      COMMON /CND2/ TC1,TC2,TC3,TC4
      COMMON /CND3/ TA,HTP,HBP,HLP
      COMMON /CND4/ TF1,TF2,TF3,TF4
      COMMON /CND5/ IRF,ICF
      COMMON /CND7/ DXC,DYC
      DIMENSION C(2,MC,NC)
      DIMENSION NFL(MC,NC)
      DIMENSION NCC(MC,NC)
      DIMENSION TF1(25),TF2(25),TF3(25),TF4(25)
      DIMENSION DX(25),DY(25),DZ(25),DXFA(25),DYFA(25),DZFA(25)
      DIMENSION DXC(25),DYC(25)
      DO 110 J=1,NC
      DYCS=0.0
      DYCM=0.0
      IF(J.NE.NC) DYCS=DYC(J)**2
      IF(J.NE.1) DYCM=DYC(J-1)**2
      DO 110 I=1,MC
      DXCS=0.0
      DXCM=0.0
      IF(I.NE.MC) DXCS=DXC(I)**2
      IF(I.NE.1) DXCM=DXC(I-1)**2
      TS=C(1,I,J)
      TSR=(TS+TABS)**4
      TAR=(TA+TABS)**4
      TFR14=(TFR1+TABS)**4
      TFR34=(TFR3+TABS)**4
      TFR44=(TFR4+TABS)**4
      NLS=NFL(I,J)
      GO TO (101,102,103,104,105),NLS
  101 CONTINUE
      QWC=(TKF*(TF1(J)-TS))/(DX(2)/2.0)
      QWR=EW*SIG*(TFR14-TSR)
      GO TO 105
  102 CONTINUE
      QWC=0.0
      QWR=0.0
      GO TO 105
  103 CONTINUE
      QWC=(TKF*(TF3(I)-TS))/(DY(2)/2.0)
      QWR=EW*SIG*(TFR34-TSR)
      GO TO 105
  104 CONTINUE
      QWC=(TKF*(TF4(I)-TS))/(DY(NM1)/2.0)
      QWR=EW*SIG*(TFR44-TSR)
      GO TO 105
  105 CONTINUE
      IF(IRF.EQ.0) QWR=0.0
      IF(ICF.EQ.0) QWC=0.0
      IF(J.EQ.NC) H=HTP
      IF(J.LT.NC) H=HLP
      QW=QWC+QWR
      QA=ES*SIG*(TAR-TSR)
      QC=H*(TA-TS)
      QS=QC+QA
      IF(I.NE.MC) C1=QW/DXC(I)
      IF(I.NE.1) C2=QW/DXC(I-1)
      IF(J.NE.NC) C3=QW/DYC(J)
      IF(J.NE.1) C4=QW/DYC(J-1)
      IF(I.NE.MC) R1=QS/DXC(I)
      IF(I.NE.1) R2=QS/DXC(I-1)
```

```
      IF(J.NE.NC) R3=QS/DYC(J)
      IF(J.NE.1) R4=QS/DYC(J-1)
      TIP=0.0
      TIM=0.0
      TJP=0.0
      TJM=0.0
      IF(I.LT.MC) TIP=C(1,I+1,J)-C(1,I,J)
      IF(I.GT.1) TIM=C(1,I-1,J)-C(1,I,J)
      IF(J.LT.NC) TJP=C(1,I,J+1)-C(1,I,J)
      IF(J.GT.1) TJM=C(1,I,J-1)-C(1,I,J)
      IF(I.NE.MC) TIP=TIP/DXCS
      IF(I.NE.1) TIM=TIM/DXCM
      IF(J.NE.NC) TJP=TJP/DYCS
      IF(J.NE.1) TJM=TJM/DYCM
      HL1=TKC*(TIP+TJP)
      HL2=TKC*(TIP+TJM)
      HL3=TKC*(TIM+TJP)
      HL4=TKC*(TIM+TJM)
      NCS=NCC(I,J)
      GO TO
     !(1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18),NCS
    1 CONTINUE
      CBC=C3
      HL=HL3+CBC
      S=(HL/TC1)+C(1,I,J)
      GO TO 20
    2 CONTINUE
      CBC=C3+C3
      HL=HL1+HL3+CBC
      S=(HL/TC2)+C(1,I,J)
      GO TO 20
    3 CONTINUE
      CBC=C2+C3
      HL=HL1+HL3+HL4+CBC
      S=(HL/TC3)+C(1,I,J)
      GO TO 20
    4 CONTINUE
      CBC=C2+C2
      HL=HL3+HL4+CBC
      S=(HL/TC2)+C(1,I,J)
      GO TO 20
    5 CONTINUE
      CBC=C2+C4
      HL=HL2+HL3+HL4+CBC
      S=(HL/TC3)+C(1,I,J)
      GO TO 20
    6 CONTINUE
      CBC=C4+C4
      HL=HL2+HL4+CBC
      S=(HL/TC2)+C(1,I,J)
      GO TO 20
    7 CONTINUE
      CBC=C4
      HL=HL4+CBC
      S=(HL/TC1)+C(1,I,J)
      GO TO 20
    8 CONTINUE
      EBC=R4
      HL=HL4+EBC
      S=(HL/TC1)+C(1,I,J)
      GO TO 20
    9 CONTINUE
      EBC=R4+R4
      HL=HL2+HL4+EBC
      S=(HL/TC2)+C(1,I,J)
      GO TO 20
```

```
 10 CONTINUE
    EBC=R1+R4
    HL=HL2+EBC
    S=(HL/TC1)+C(1,I,J)
    GO TO 20
 11 CONTINUE
    EBC=R1+R1
    HL=HL1+HL2+EBC
    S=(HL/TC2)+C(1,I,J)
    GO TO 20
 12 CONTINUE
    EBC=R1
    HL=HL1+EBC
    S=(HL/TC1)+C(1,I,J)
    GO TO 20
 13 CONTINUE
    HL=HL1+HL3
    S=(HL/TC2)+C(1,I,J)
    GO TO 20
 14 CONTINUE
    HL=HL3
    S=(HL/TC1)+C(1,I,J)
    GO TO 20
 15 CONTINUE
    HL=HL3+HL4
    S=(HL/TC2)+C(1,I,J)
    GO TO 20
 16 CONTINUE
    HL=HL3+HL4
    S=(HL/TC2)+C(1,I,J)
    GO TO 20
 17 CONTINUE
    HL=HL1+HL2+HL3+HL4
    S=(HL/TC4)+C(1,I,J)
    GO TO 20
 18 CONTINUE
    GO TO 110
 20 CONTINUE
    C(2,I,J)=S
110 CONTINUE
    DO 120 J=1,NC
    DO 120 I=1,MC
    C(1,I,J)=C(2,I,J)
120 CONTINUE
    RETURN
    END
```

```
      SUBROUTINE AST(C,I2,I3,J2,J3,J4)
      DIMENSION C(2,I3,J4)
      I1=1
      J1=1
      I1P=I1+1
      I2P=I2+1
      IES=2*(I3-I1)+J4
      IIS=2*(I3-I2)+(J3-J2+1)
      SBE=0.0
      STE=0.0
      DO 10 I=I1P,I3
      SBE=SBE+C(2,I,J1)
      STE=STE+C(2,I,J4)
   10 CONTINUE
      SSE=0.0
      DO 15 J=J1,J4
      SSE=SSE+C(2,I1,J)
   15 CONTINUE
      TES=(SBE+STE+SSE)/FLOAT(IES)
      SBI=0.0
      STI=0.0
      DO 20 I=I2P,I3
      SBI=SBI+C(2,I,J2)
      STI=STI+C(2,I,J3)
      SSI=0.0
   20 CONTINUE
      DO 25 J=J2,J3
      SSI=SSI+C(2,I2,J)
   25 CONTINUE
      TIS=(SBI+STI+SSI)/FLOAT(IIS)
      WRITE(6,30) (TES-273.0)
   30 FORMAT(' TES=',E12.5)
      WRITE(6,35) (TIS-273.0)
   35 FORMAT(' TIS=',E12.5)
      RETURN
      END
```

```
      SUBROUTINE PMS(U,V,W)
      COMMON /BL2/ R,B,VK,THD,CP
      COMMON /BL6/ M,N,L
      COMMON /BL9/ ND
      COMMON /BL10/ I,J,K
      COMMON /BL51/ FKU,FKV,FKW
      COMMON /BL53/ TDIA
      COMMON /BL54/ RD1,RD2,RD3,RD4
      COMMON /BL55/ CST1,CST2,CST3,CST4
      COMMON /BL56/ EX2,EX3,EX4
      COMMON /BL57/ UC,VC,WC
      DIMENSION U(M,N,L),V(M,N,L),W(M,N,L)
      IF(ND.GT.0) UC=0.5*(U(I,J,K)+U(I-1,J,K))
      IF(ND.GT.1) VC=0.5*(V(I,J,K)+V(I,J-1,K))
      IF(ND.GT.2) WC=0.5*(W(I,J,K)+W(I,J,K-1))
      TVEL=SQRT(UC*UC+VC*VC+WC*WC)
      GO TO (83,82,81),ND
   81 CONTINUE
      RDW=(TVEL*TDIA)/VK
      IF(RDW.LE.RD1) FKW=CST1*TDIA**2
      IF(RDW.GT.RD1.AND.RDW.LE.RD2) FKW=CST2*RDW**(-EX2)*TDIA**2
      IF(RDW.GT.RD2.AND.RDW.LE.RD3) FKW=CST3*RDW**(-EX3)*TDIA**2
      IF(RDW.GT.RD3) FKW=CST4*RDW**(-EX4)*TDIA**2
   82 CONTINUE
      RDV=(TVEL*TDIA)/VK
      IF(RDV.LE.RD1) FKV=CST1*TDIA**2
      IF(RDV.GT.RD1.AND.RDV.LE.RD2) FKV=CST2*RDV**(-EX2)*TDIA**2
      IF(RDV.GT.RD2.AND.RDV.LE.RD3) FKV=CST3*RDV**(-EX3)*TDIA**2
      IF(RDV.GT.RD3) FKV=CST4*RDV**(-EX4)*TDIA**2
   83 CONTINUE
      RDU=(TVEL*TDIA)/VK
      IF(RDU.LE.RD1) FKU=CST1*TDIA**2
      IF(RDU.GT.RD1.AND.RDU.LE.RD2) FKU=CST2*RDU**(-EX2)*TDIA**2
      IF(RDU.GT.RD2.AND.RDU.LE.RD3) FKU=CST3*RDU**(-EX3)*TDIA**2
      IF(RDU.GT.RD3) FKU=CST4*RDU**(-EX4)*TDIA**2
      RETURN
      END
```

```
      SUBROUTINE US(A,U,V,W,P)
      COMMON /BL1/ DX,DY,DZ,DXFA,DYFA,DZFA
      COMMON /BL2/ R,B,VK,THD,CP
      COMMON /BL4/ DT
      COMMON /BL6/ M,N,L
      COMMON /BL7/ MM1,NM1,LM1,MM2,NM2,LM2
      COMMON /BL8/ TR,G
      COMMON /BL9/ ND
      COMMON /BL10/ I,J,K
      COMMON /BL51/ FKU,FKV,FKW
      COMMON /BL60/ IFU,IFV,IFW,IFT
      COMMON /BL61/ EPR
      DIMENSION A(4,M,N,L),U(M,N,L),V(M,N,L),W(M,N,L),P(M,N,L)
      DIMENSION DX(25),DY(25),DZ(25),DXFA(25),DYFA(25),DZFA(25)
      GO TO (3,2,1),ND
    1 CONTINUE
      WA=(DX(I)*(W(I,J,K-1)+W(I,J,K))+DX(I+1)*(W(I+1,J,K-1)+
     'W(I+1,J,K)))/(4*DXFA(I))
      FFUZ=(U(I,J,K+1)-U(I,J,K))/DZFA(K)
      BFUZ=(U(I,J,K)-U(I,J,K-1))/DZFA(K-1)
      WFUZ=(FFUZ*(WA-ABS(WA))/2)+(BFUZ*(WA+ABS(WA))/2)
      SUZ=2*(FFUZ-BFUZ)/(DZFA(K)+DZFA(K-1))
    2 CONTINUE
      VA=(DX(I)*(V(I,J,K)+V(I,J-1,K))+DX(I+1)*(V(I+1,J,K)+
     'V(I+1,J-1,K)))/(4*DXFA(I))
      FFUY=(U(I,J+1,K)-U(I,J,K))/DYFA(J)
      BFUY=(U(I,J,K)-U(I,J-1,K))/DYFA(J-1)
      VFUY=(FFUY*(VA-ABS(VA))/2)+(BFUY*(VA+ABS(VA))/2)
      SUY=2*(FFUY-BFUY)/(DYFA(J)+DYFA(J-1))
    3 CONTINUE
      UA=U(I,J,K)
      FFUX=(U(I+1,J,K)-U(I,J,K))/DX(I+1)
      BFUX=(U(I,J,K)-U(I-1,J,K))/DX(I)
      UFUX=(FFUX*(UA-ABS(UA))/2)+(BFUX*(UA+ABS(UA))/2)
      FPX=(P(I,J,K)-P(I+1,J,K))/DXFA(I)
      SUX=(FFUX-BFUX)/DXFA(I)
      GO TO (11,12),IFU
   11 CONTINUE
      A(1,I,J,K)=U(I,J,K)+DT*(FPX-UFUX-VFUY-WFUZ+
     'VK*(SUX+SUY+SUZ))
      GO TO 13
   12 CONTINUE
      A(1,I,J,K)=U(I,J,K)+DT*(FPX-UFUX-VFUY-WFUZ
     '-EPR*(VK/FKU)*UA)
   13 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE VS(A,U,V,W,P,T)
      COMMON /BL1/ DX,DY,DZ,DXFA,DYFA,DZFA
      COMMON /BL2/ R,B,VK,THD,CP
      COMMON /BL4/ DT
      COMMON /BL6/ M,N,L
      COMMON /BL7/ MM1,NM1,LM1,MM2,NM2,LM2
      COMMON /BL8/ TR,G
      COMMON /BL9/ ND
      COMMON /BL10/ I,J,K
      COMMON /BL51/ FKU,FKV,FKW
      COMMON /BL60/ IFU,IFV,IFW,IFT
      COMMON /BL61/ EPR
      DIMENSION A(4,M,N,L),U(M,N,L),V(M,N,L),W(M,N,L),P(M,N,L),T(M,N,L)
      DIMENSION DX(25),DY(25),DZ(25),DXFA(25),DYFA(25),DZFA(25)
      GO TO(3,2,1),ND
    1 CONTINUE
      WA=(DY(J)*(W(I,J,K)+W(I,J,K-1))+DY(J+1)*(W(I,J+1,K)+
     'W(I,J+1,K-1)))/(4*DYFA(J))
      FFVZ=(V(I,J,K+1)-V(I,J,K))/DZFA(K)
      BFVZ=(V(I,J,K)-V(I,J,K-1))/DZFA(K-1)
      WFVZ=(FFVZ*(WA-ABS(WA))/2)+(BFVZ*(WA+ABS(WA))/2)
      SVZ=2*(FFVZ-BFVZ)/(DZFA(K-1)+DZFA(K))
    2 CONTINUE
      VA=V(I,J,K)
      FFVY=(V(I,J+1,K)-V(I,J,K))/DY(J+1)
      BFVY=(V(I,J,K)-V(I,J-1,K))/DY(J)
      VFVY=(FFVY*(VA-ABS(VA))/2)+(BFVY*(VA+ABS(VA))/2)
      FPY=(P(I,J,K)-P(I,J+1,K))/DYFA(J)
      RV1=DY(J+1)/(2*DYFA(J))
      RV2=DY(J)/(2*DYFA(J))
      BFY=G*B*(T(I,J+1,K)*RV1+T(I,J,K)*RV2-TR)
      SVY=(FFVY-BFVY)/DYFA(J)
    3 CONTINUE
      UA=(DY(J)*(U(I-1,J,K)+U(I,J,K))+DY(J+1)*(U(I-1,J+1,K)+
     'U(I,J+1,K)))/(4*DYFA(J))
      FFVX=(V(I+1,J,K)-V(I,J,K))/DXFA(I)
      BFVX=(V(I,J,K)-V(I-1,J,K))/DXFA(I-1)
      UFVX=(FFVX*(UA-ABS(UA))/2)+(BFVX*(UA+ABS(UA))/2)
      SVX=2*(FFVX-BFVX)/(DXFA(I-1)+DXFA(I))
      GO TO (11,12),IFV
   11 CONTINUE
      A(2,I,J,K)=V(I,J,K)+DT*(FPY-UFVX-VFVY-WFVZ+BFY+
     'VK*(SVX+SVY+SVZ))
      GO TO 13
   12 CONTINUE
      A(2,I,J,K)=V(I,J,K)+DT*(FPY-UFVX-VFVY-WFVZ+EPR*BFY
     '-EPR*(VK/FKV)*VA)
   13 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE PS(A,P,DFDP)
      COMMON /BL1/ DX,DY,DZ,DXFA,DYFA,DZFA
      COMMON /BL4/ DT
      COMMON /BL6/ M,N,L
      COMMON /BL7/ MM1,NM1,LM1,MM2,NM2,LM2
      COMMON /BL9/ ND
      COMMON /BL52/ SPD
      COMMON /BL58/ IS,IE,JS,JE,KS,KE
      COMMON /BL59/ TOL,CRT,ITM,NGP,ITER
      DIMENSION A(4,M,N,L)
      DIMENSION P(M,N,L)
      DIMENSION DFDP(M,N,L)
      DIMENSION DX(25),DY(25),DZ(25),DXFA(25),DYFA(25),DZFA(25)
      K=1
      ITER=0
      D1=0.0
      D2=0.0
      D3=0.0
   16 CONTINUE
      ITER=ITER+1
      SUM=0.0
      DO 20 J=2,NM1
      DO 20 I=2,MM1
      KS=2
      KE=LM1
      JS=2
      JE=NM1
      IS=2
      IE=MM1
      IF(ND.GT.0) D1=(A(1,I,J,K)-A(1,I-1,J,K))/DX(I)
      IF(ND.GT.1) D2=(A(2,I,J,K)-A(2,I,J-1,K))/DY(J)
      IF(ND.GT.2) D3=(A(3,I,J,K)-A(3,I,J,K-1))/DZ(K)
      D=D1+D2+D3
      SUM=SUM+ABS(D)
      DP=SPD*(-D/DFDP(I,J,K))
      P(I,J,K)=P(I,J,K)+DP
      DPDT=DP*DT
      GO TO (3,2,1),ND
    1 CONTINUE
      IF(K.GT.KS) A(3,I,J,K-1)=A(3,I,J,K-1)-DPDT/DZFA(K-1)
      IF(K.LT.KE) A(3,I,J,K)=A(3,I,J,K)+DPDT/DZFA(K)
    2 CONTINUE
      IF(J.GT.JS) A(2,I,J-1,K)=A(2,I,J-1,K)-DPDT/DYFA(J-1)
      IF(J.LT.JE) A(2,I,J,K)=A(2,I,J,K)+DPDT/DYFA(J)
    3 CONTINUE
      IF(I.GT.IS) A(1,I-1,J,K)=A(1,I-1,J,K)-DPDT/DXFA(I-1)
      IF(I.LT.IE) A(1,I,J,K)=A(1,I,J,K)+DPDT/DXFA(I)
   20 CONTINUE
      CRT=SUM/FLOAT(NGP)
      IF(ITER.GT.ITM) GO TO 27
      IF(CRT.GT.TOL) GO TO 16
   27 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE VBC(A)
      COMMON /BL1/ DX,DY,DZ,DXFA,DYFA,DZFA
      COMMON /BL6/ M,N,L
      COMMON /BL7/ MM1,NM1,LM1,MM2,NM2,LM2
      DIMENSION A(4,M,N,L)
      DIMENSION DX(25),DY(25),DZ(25),DXFA(25),DYFA(25),DZFA(25)
      K=1
      I=1
      DO 1 J=2,NM1
      A(1,I,J,K)=0.0
      A(2,I,J,K)=-A(2,I+1,J,K)
    1 CONTINUE
      I=M
      DO 2 J=2,NM1
      A(1,I-1,J,K)=0.0
      A(2,I,J,K)=A(2,I-1,J,K)
    2 CONTINUE
      J=1
      DO 3 I=1,M
      A(1,I,J,K)=-A(1,I,J+1,K)
      A(2,I,J,K)=0.0
    3 CONTINUE
      J=N
      DO 4 I=1,M
      A(1,I,J,K)=-A(1,I,J-1,K)
      A(2,I,J-1,K)=0.0
    4 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE TAVW(C,IA,JA,JB,MC,NC)
      COMMON /BL86/ TWR1,TWR3,TWR4
      DIMENSION C(2,MC,NC)
      ICNT=0
      SUMW1=0.0
      DO 10 J=JA,JB
      ICNT=ICNT+1
      SUMW1=SUMW1+C(1,IA,J)
   10 CONTINUE
      TWR1=SUMW1/FLOAT(ICNT)
      ICNT=0
      SUMW3=0.0
      SUMW4=0.0
      DO 20 I=IA,MC
      ICNT=ICNT+1
      SUMW3=SUMW3+C(1,I,JA)
      SUMW4=SUMW4+C(1,I,JB)
   20 CONTINUE
      TWR3=SUMW3/FLOAT(ICNT)
      TWR4=SUMW4/FLOAT(ICNT)
      RETURN
      END
```

```
      SUBROUTINE RAD(NCR,T,QR,EHC)
      COMMON /BL1/ DX,DY,DZ,DXFA,DYFA,DZFA
      COMMON /BL6/ M,N,L
      COMMON /BL83/ SIG,TABS
      COMMON /BL84/ EB,EM
      COMMON /BL85/ M1,M2,N1,N2
      COMMON /BL86/ TWR1,TWR3,TWR4
      DIMENSION DX(25),DY(25),DZ(25),DXFA(25),DYFA(25),DZFA(25)
      DIMENSION T(M,N,L),QR(M,N,L)
      DIMENSION NCR(M,N,L)
      K=1
      TWR=(TWR1+TWR3+TWR4)/3.0
      TAS=(TWR+TABS)**4
      DO 20 J=N1,N2
      DO 20 I=M1,M2
      AXZ=DX(I)
      AYZ=DY(J)
      DV=DX(I)*DY(J)
      IFR=NCR(I,J,K)
      TES=(T(I,J,K)+TABS)**4
      GO TO (1,2,3,4,5,6,7,8,9),IFR
    1 CONTINUE
      AS=AXZ+AYZ
      AF=AXZ+AYZ
      TAV=(T(I+1,J,K)+T(I,J+1,K))/2.0
      GO TO 10
    2 CONTINUE
      AS=AYZ
      AF=2.0*AXZ+AYZ
      TAV=(T(I+1,J,K)+T(I,J+1,K)+T(I,J-1,K))/3.0
      GO TO 10
    3 CONTINUE
      AS=AXZ+AYZ
      AF=AXZ+AYZ
      TAV=(T(I+1,J,K)+T(I,J-1,K))/2.0
      GO TO 10
    4 CONTINUE
      AS=AXZ
      AF=AXZ+2.0*AYZ
      TAV=(T(I+1,J,K)+T(I-1,J,K)+T(I,J+1,K))/3.0
      GO TO 10
    5 CONTINUE
      AS=0.0
      AF=2.0*AXZ+2.0*AYZ
      TAV=(T(I+1,J,K)+T(I-1,J,K)+T(I,J+1,K)+T(I,J-1,K))/4.0
      GO TO 10
    6 CONTINUE
      AS=AXZ
      AF=AXZ+2.0*AYZ
      TAV=(T(I+1,J,K)+T(I-1,J,K)+T(I,J-1,K))/3.0
      GO TO 10
    7 CONTINUE
      AS=AXZ
      AF=AXZ+AYZ
      TAV=(T(I-1,J,K)+T(I,J+1,K))/2.0
      GO TO 10
    8 CONTINUE
      AS=0.0
      AF=2.0*AXZ+AYZ
      TAV=(T(I-1,J,K)+T(I,J+1,K)+T(I,J-1,K))/3.0
      GO TO 10
    9 CONTINUE
      AS=AXZ
      AF=AXZ+AYZ
      TAV=(T(I-1,J,K)+T(I,J-1,K))/2.0
   10 CONTINUE
```

```
      TAB=(TAV+TABS)**4
      QR1=(SIG*EB*AF*(TES-TAB))/DV
      QR2=(SIG*EM*AS*(TES-TAS))/DV
      QR(I,J,K)=(QR1+QR2)/EHC
   20 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE TS(A,U,V,W,T,Q,QR)
      COMMON /BL1/ DX,DY,DZ,DXFA,DYFA,DZFA
      COMMON /BL2/ R,B,VK,THD,CP
      COMMON /BL3/ CR,ETD
      COMMON /BL4/ DT
      COMMON /BL6/ M,N,L
      COMMON /BL7/ MM1,NM1,LM1,MM2,NM2,LM2
      COMMON /BL8/ TR,G
      COMMON /BL9/ ND
      COMMON /BL10/ I,J,K
      COMMON /BL60/ IFU,IFV,IFW,IFT
      COMMON /BL61/ EPR
      DIMENSION A(4,M,N,L),U(M,N,L),V(M,N,L),W(M,N,L),T(M,N,L)
      DIMENSION Q(M,N,L)
      DIMENSION QR(M,N,L)
      DIMENSION DX(25),DY(25),DZ(25),DXFA(25),DYFA(25),DZFA(25)
      GO TO(3,2,1),ND
    1 CONTINUE
      WA=(W(I,J,K)+W(I,J,K-1))/2
      FFTZ=(T(I,J,K+1)-T(I,J,K))/DZFA(K)
      BFTZ=(T(I,J,K)-T(I,J,K-1))/DZFA(K-1)
      WFTZ=(FFTZ*(WA-ABS(WA))/2)+(BFTZ*(WA+ABS(WA))/2)
      STZ=2*(FFTZ-BFTZ)/(DZFA(K-1)+DZFA(K))
    2 CONTINUE
      VA=(V(I,J,K)+V(I,J-1,K))/2
      FFTY=(T(I,J+1,K)-T(I,J,K))/ DYFA(J)
      BFTY=(T(I,J,K)-T(I,J-1,K))/DYFA(J-1)
      VFTY=(FFTY*(VA-ABS(VA))/2)+(BFTY*(VA+ABS(VA))/2)
      STY=2*(FFTY-BFTY)/(DYFA(J-1)+DYFA(J))
    3 CONTINUE
      UA=(U(I,J,K)+U(I-1,J,K))/2
      FFTX=(T(I+1,J,K)-T(I,J,K))/DXFA(I)
      BFTX=(T(I,J,K)-T(I-1,J,K))/DXFA(I-1)
      UFTX=(FFTX*(UA-ABS(UA))/2)+(BFTX*(UA+ABS(UA))/2)
      STX=2*(FFTX-BFTX)/(DXFA(I-1)+DXFA(I))
      GO TO (11,12),IFT
   11 CONTINUE
      A(4,I,J,K)=T(I,J,K)+DT*(Q(I,J,K)-UFTX-VFTY-WFTZ+
     'THD*(STX+STY+STZ))
      GO TO 13
   12 CONTINUE
      A(4,I,J,K)=T(I,J,K)+DT*(Q(I,J,K)-CR*(UFTX+VFTY+WFTZ)
     '+ETD*(STX+STY+STZ)-QR(I,J,K))
   13 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE ET(C,IA,JA,JB,MC,NC)
      COMMON /BL5/ T1,T2,T3,T4
      COMMON /BL7/ MM1,NM1,LM1,MM2,NM2,LM2
      DIMENSION C(2,MC,NC)
      DIMENSION T1(25),T2(25),T3(25),T4(25)
      DO 10 J=2,NM1
      JM=JA+J-2
      JP=JM+1
      T1(J)=(C(1,IA,JM)+C(1,IA,JP))/2.0
      T2(J)=(C(1,MC,JM)+C(1,MC,JP))/2.0
   10 CONTINUE
      DO 20 I=2,MM1
      IM=IA+I-2
      IP=IM+1
      T3(I)=(C(1,IM,JA)+C(1,IP,JA))/2.0
      T4(I)=(C(1,IM,JB)+C(1,IP,JB))/2.0
   20 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE TBC1(A)
      COMMON /BL5/ T1,T2,T3,T4
      COMMON /BL6/ M,N,L
      COMMON /BL7/ MM1,NM1,LM1,MM2,NM2,LM2
      COMMON /BLS/ S1,S2,S3,S4
      DIMENSION A(4,M,N,L)
      DIMENSION T1(25),T2(25),T3(25),T4(25)
      K=1
      I=1
      DO 1 J=2,NM1
      A(4,I,J,K)=T1(J)-S1*(A(4,I+1,J,K)-T1(J))
    1 CONTINUE
      I=M
      DO 2 J=2,NM1
      A(4,I,J,K)=A(4,I-1,J,K)
    2 CONTINUE
      J=1
      DO 3 I=1,M
      A(4,I,J,K)=T3(I)-S3*(A(4,I,J+1,K)-T3(I))
    3 CONTINUE
      J=N
      DO 4 I=1,M
      A(4,I,J,K)=T4(I)-S4*(A(4,I,J-1,K)-T4(I))
    4 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE TBC2(A)
      COMMON /BL5/ T1,T2,T3,T4
      COMMON /BL6/ M,N,L
      COMMON /BL7/ MM1,NM1,LM1,MM2,NM2,LM2
      COMMON /BL11/ A11,A12,A13,X33,XM323,XP323
      COMMON /BL12/ A11M,A12M,A13M,X33M,XM323M,XP323M
      COMMON /BL21/ B11,B12,B13,Y33,YM323,YP323
      COMMON /BL22/ B11N,B12N,B13N,Y33N,YM323N,YP323N
      DIMENSION A(4,M,N,L)
      DIMENSION T1(25),T2(25),T3(25),T4(25)
      K=1
      I=1
      DO 1 J=2,NM1
      TDH=A(4,I+1,J,K)-A(4,I+2,J,K)
      AH=A11*(T1(J)-A(4,I+2,J,K))+A12*TDH+A13*TDH
      A(4,I,J,K)=A(4,I+2,J,K)-AH*X33-XM323*TDH+AH*XP323
    1 CONTINUE
      I=M
      DO 2 J=2,NM1
      TDC=A(4,I-1,J,K)-A(4,I-2,J,K)
      AC=A11M*(T2(J)-A(4,I-2,J,K))+A12M*TDC+A13M*TDC
      A(4,I,J,K)=A(4,I-2,J,K)-AC*X33M-XM323M*TDC+AC*XP323M
      A(4,I,J,K)=A(4,I-1,J,K)
    2 CONTINUE
      J=1
      DO 3 I=1,M
      TDB=A(4,I,J+1,K)-A(4,I,J+2,K)
      AB=B11*(T3(I)-A(4,I,J+2,K))+B12*TDB+B13*TDB
      A(4,I,J,K)=A(4,I,J+2,K)-AB*Y33-YM323*TDB+AB*YP323
    3 CONTINUE
      J=N
      DO 4 I=1,M
      TDT=A(4,I,J-1,K)-A(4,I,J-2,K)
      AT=B11N*(T4(I)-A(4,I,J-2,K))+B12N*TDT+B13N*TDT
      A(4,I,J,K)=A(4,I,J-2,K)-AT*Y33N-YM323N*TDT+AT*YP323N
    4 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE WRITE(TIMC,TIME,C,U,V,W,T,P,MC,NC)
      COMMON /BL6/ M,N,L
      DIMENSION C(2,MC,NC)
      DIMENSION U(M,N,L),V(M,N,L),W(M,N,L),T(M,N,L)
      DIMENSION P(M,N,L)
      WRITE(9,30) TIMC
      DO 10 J=1,NC
      DO 10 I=1,MC
      WRITE(9,30) C(1,I,J)
   10 CONTINUE
      WRITE(9,30) TIME
      DO 20 K=1,L
      DO 20 J=1,N
      DO 20 I=1,M
      WRITE(9,40)
     !U(I,J,K),V(I,J,K),W(I,J,K),T(I,J,K),P(I,J,K)
   20 CONTINUE
   30 FORMAT(E14.5)
   40 FORMAT(5E14.5)
      RETURN
      END
```

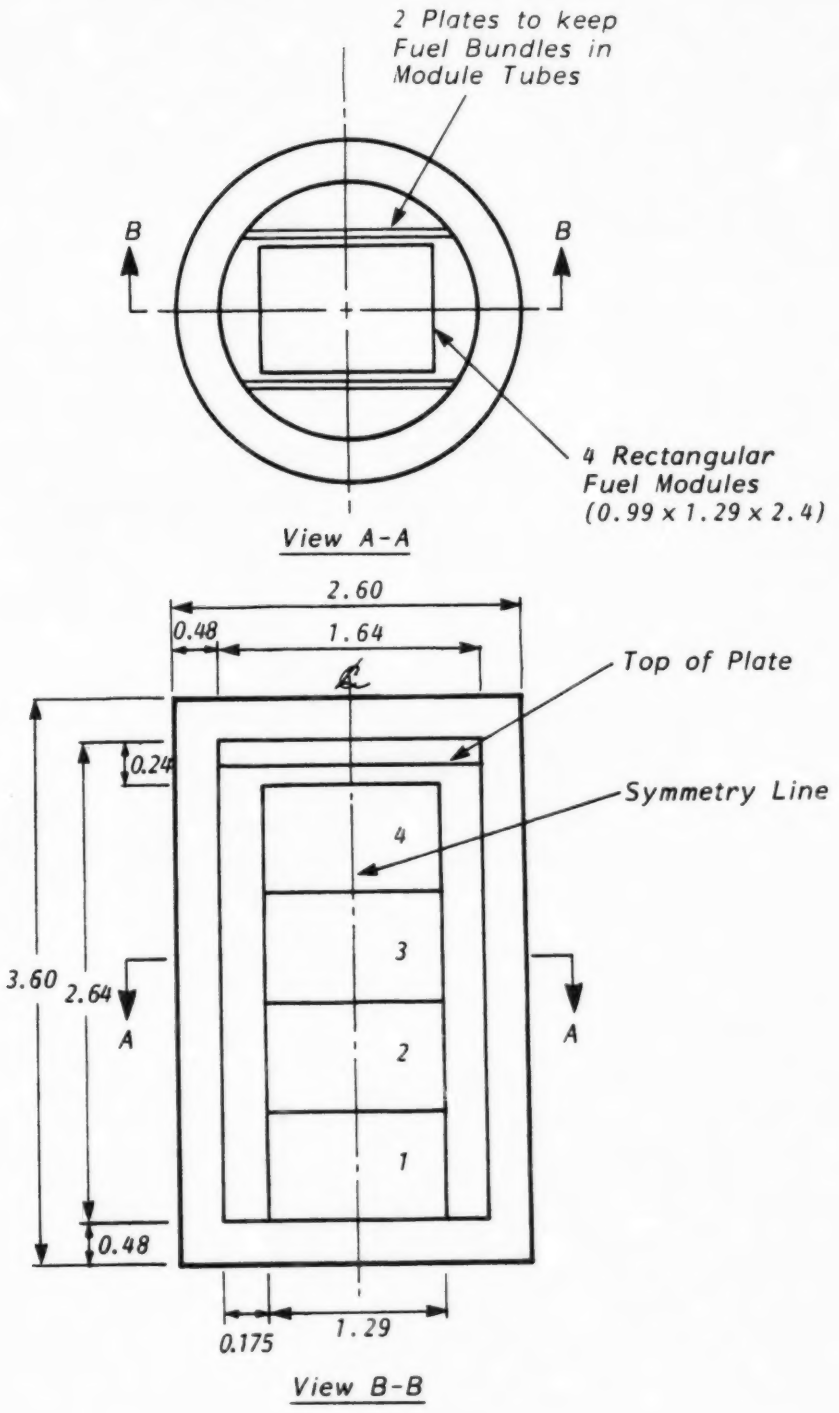


FIGURE 1

SCHEMATIC DIAGRAM OF CONCRETE INTEGRATED CASK

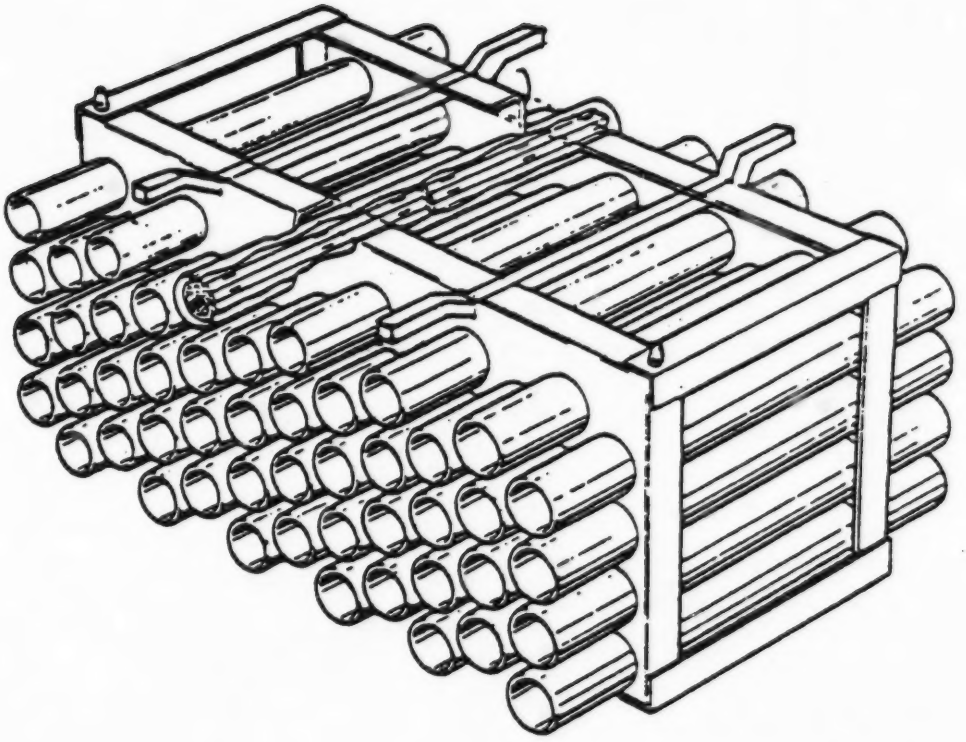


FIGURE 2

IRRADIATED FUEL STORAGE MODULE
(1.29 m x 0.99m x 0.6 m)

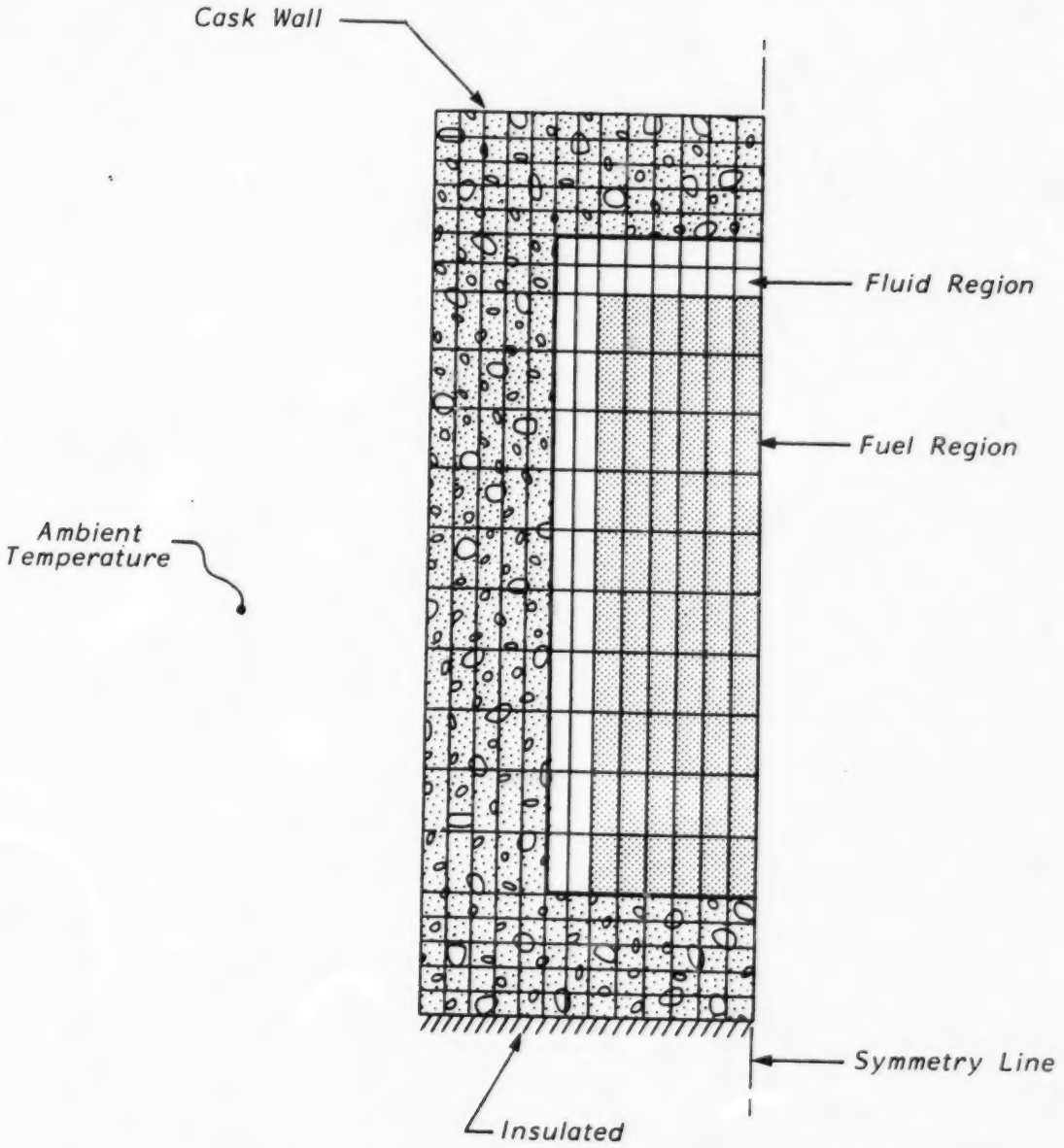


FIGURE 3
FINITE DIFFERENCE MESH FOR CONCRETE INTEGRATED CASK

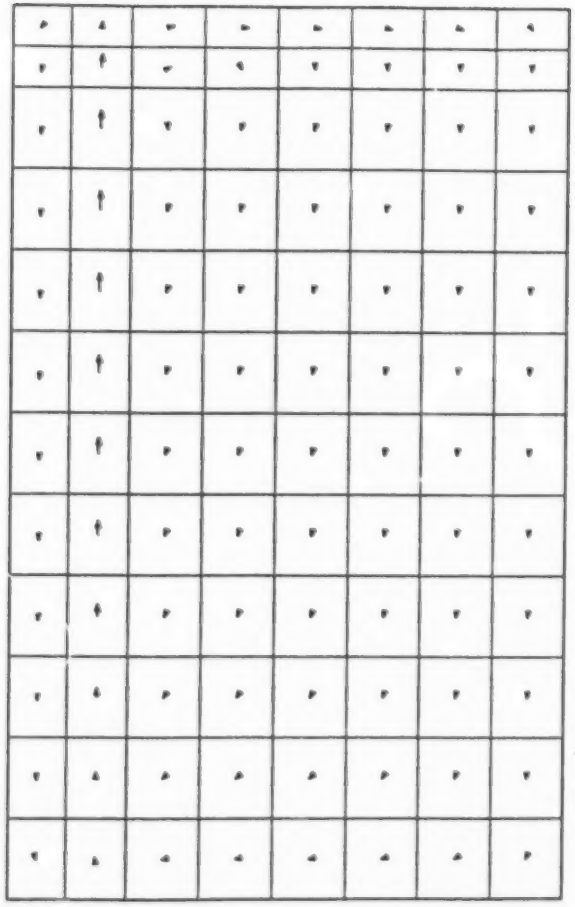
42.0	42.9	43.7	44.6	45.3	46.0	46.5	46.8	47.2	47.5	47.7	47.8	47.9	47.9
43.0	44.1	45.2	46.2	47.2	48.0	48.6	49.0	49.5	49.9	50.1	50.2	50.3	50.3
44.0	45.3	46.6	47.9	49.2	50.2	50.9	51.4	52.0	52.3	52.6	52.7	52.8	52.8
45.0	46.5	48.1	49.7	51.3	52.6	53.4	54.0	54.6	54.9	55.2	55.3	55.4	55.4
46.0	47.7	49.6	51.6	53.6	55.5	56.3	56.8	57.3	57.6	57.8	57.9	58.0	58.0
46.8	48.8	51.0	53.3	56.0	59.3	59.4	59.7	60.2	60.4	60.5	60.6	60.6	60.6
48.0	50.2	52.8	55.6	59.0	63.2								
48.8	51.3	54.0	57.1	60.7	64.9								
50.8	53.8	56.8	60.1	63.7	67.5								
52.0	55.1	58.3	61.6	65.1	68.7								
52.5	55.8	59.1	62.4	65.8	69.3								
52.8	56.1	59.5	62.8	66.2	69.6								
53.0	56.3	59.7	63.0	66.4	69.8								
53.1	56.5	59.8	63.2	66.5	69.9								
53.2	56.6	60.0	63.3	66.7	70.0								
53.4	56.8	60.2	63.6	66.9	70.2								
53.7	57.1	60.6	64.1	67.5	70.8								
53.9	57.4	61.1	64.8	68.8	73.2	78.1	80.7	83.1	84.8	85.9	86.6	87.0	87.1
53.9	57.4	61.0	64.7	68.5	72.4	75.7	78.2	80.9	82.8	84.2	85.0	85.6	85.7
53.8	57.4	60.9	64.5	68.0	71.5	74.2	76.5	79.3	81.3	82.8	83.8	84.4	84.6
53.8	57.3	60.8	64.2	67.6	70.9	73.3	75.5	78.2	80.3	81.8	82.9	83.5	83.7
53.7	57.2	60.7	64.1	67.3	70.5	72.8	74.9	77.5	79.7	81.2	82.4	83.0	83.2
53.7	57.2	60.6	64.0	67.3	70.3	72.7	74.7	77.3	79.4	81.1	82.2	82.8	83.0

Ambient Temperature = 38°C

Decay Heat = 6 W/Bundle

FIGURE 4

TEMPERATURE DISTRIBUTION (°C)
ACROSS CASK WALL FOR CASE #1



65.	77.	77.	76.	73.	69.	66.	62.
67.	79.	79.	77.	73.	70.	66.	62.
68.	81.	79.	78.	74.	71.	68.	65.
68.	81.	79.	79.	76.	73.	70.	67.
69.	81.	80.	80.	76.	75.	72.	70.
69.	81.	81.	82.	80.	77.	74.	72.
69.	81.	82.	84.	82.	80.	77.	76.
69.	81.	84.	86.	85.	82.	80.	79.
69.	81.	86.	88.	87.	86.	84.	83.
70.	81.	88.	91.	91.	89.	88.	87.
70.	81.	91.	94.	94.	93.	92.	92.
71.	81.	91.	93.	93.	93.	93.	93.

Ambient Temperature = 38°C
Decay Head = 6 W/Bundle

T_F = 94°C + 2°C = 96°C

FIGURE 5

VELOCITY PLOT AND TEMPERATURE DISTRIBUTION (°C) WITHIN CASK CAVITY FOR CASE #1

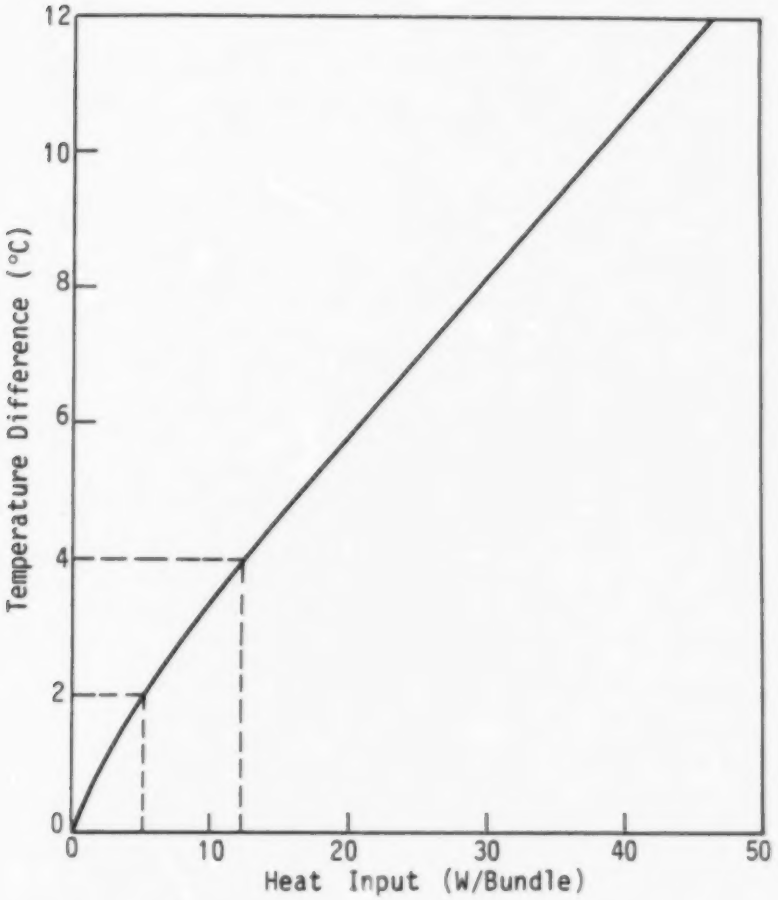


FIGURE 6

TEMPERATURE DIFFERENCE BETWEEN MAXIMUM FUEL SHEATH TEMPERATURE AND AVERAGE MODULE TUBE/FUEL BUNDLE TEMPERATURE DETERMINED FROM EXPERIMENTAL RESULTS/2/

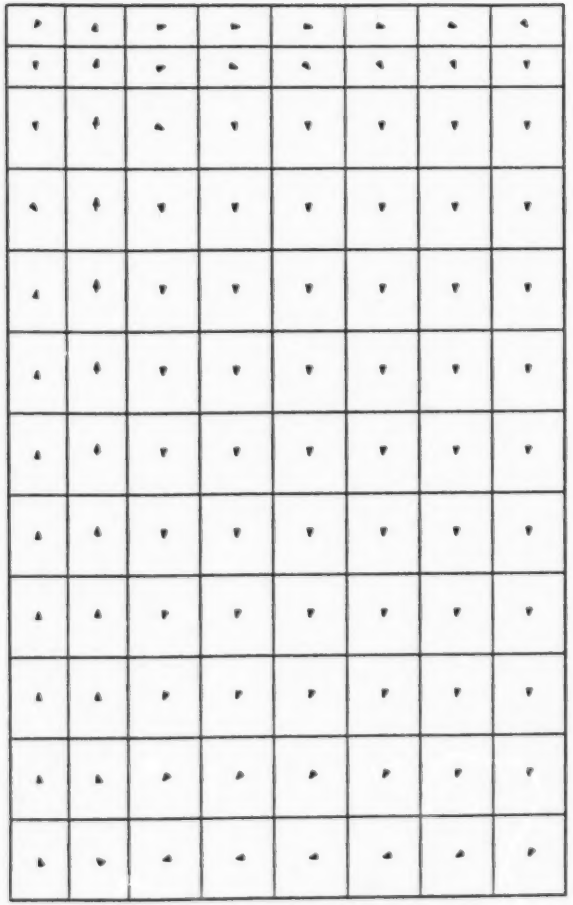
-18.2	-17.1	-15.9	-14.8	-13.7	-12.8	-12.2	-11.7	-11.2	-10.8	-10.6	-10.5	-10.4	-10.4
-17.0	-15.1	-13.2	-11.3	-9.5	-8.0	-6.9	-6.1	-5.2	-4.7	-4.3	-4.1	-4.0	-4.0
-15.8	-13.2	-10.5	-7.8	-5.2	-2.8	-1.3	-0.2	0.9	1.6	2.0	2.3	2.4	2.5
-14.7	-11.3	-7.8	-4.2	-0.5	2.9	4.9	6.2	7.4	8.2	8.6	8.8	9.0	9.0
-13.6	-9.6	-5.2	-0.6	4.4	9.5	11.9	13.2	14.3	14.9	15.3	15.5	15.6	15.6
-12.8	-8.0	-3.0	2.7	9.4	18.2	20.1	21.0	21.6	21.9	22.1	22.2	22.2	22.2
-11.7	-6.3	-0.4	6.1	13.7	22.8								
-11.0	-5.1	1.1	8.0	15.6	24.1								
-9.8	-3.2	3.6	10.6	17.9	25.4								
-9.3	-2.5	4.5	11.5	18.6	25.8								
-9.1	-2.2	4.8	11.8	18.9	25.9								
-9.1	-2.1	4.9	11.9	19.0	26.0								
-9.1	-2.1	5.0	12.0	19.0	26.0								
-9.1	-2.1	5.0	12.0	19.0	26.0								
-9.1	-2.1	4.9	11.9	19.0	26.0								
-9.2	-2.3	4.7	11.7	18.8	26.0								
-9.4	-2.7	4.2	11.2	18.4	25.7								
-10.0	-3.6	2.9	9.6	16.8	25.2	31.6	33.9	35.4	36.3	36.9	37.2	37.4	37.4
-10.2	-3.9	2.4	8.8	15.4	21.9	26.5	29.5	32.1	33.8	34.9	35.6	36.0	36.1
-10.4	-4.2	1.9	8.0	13.9	19.5	23.4	26.4	29.6	31.8	33.3	34.2	34.8	34.9
-10.5	-4.5	1.5	7.3	12.8	17.9	21.5	24.5	27.9	30.3	32.0	33.2	33.8	34.0
-10.6	-4.7	1.1	6.8	12.1	16.9	20.5	23.4	26.8	29.4	31.3	32.5	33.3	33.5
-10.7	-4.7	1.0	6.6	11.9	16.6	20.1	23.0	26.5	29.1	31.0	32.3	33.1	33.3

Ambient Temperature = -20°C

Decay Heat = 6 W/Bundle

FIGURE 7

TEMPERATURE DISTRIBUTION (°C)
ACROSS CASK WALL FOR CASE #2



22.	27.	28.	27.	26.	25.	24.	23.
22.	29.	29.	28.	27.	26.	25.	23.
23.	32.	30.	30.	28.	29.	27.	26.
25.	33.	31.	31.	31.	31.	30.	29.
27.	34.	31.	33.	33.	33.	32.	31.
28.	34.	31.	34.	35.	35.	34.	34.
29.	35.	32.	35.	36.	37.	36.	36.
30.	35.	32.	36.	36.	36.	36.	36.
31.	35.	33.	37.	39.	40.	40.	41.
31.	36.	35.	39.	41.	42.	42.	42.
31.	35.	36.	40.	42.	42.	42.	43.
30.	35.	36.	36.	39.	39.	40.	40.

Ambient Temperature = -20°C

Decay Heat = 6 W/Bundle

T_F = 43°C + 2°C = 45°C

FIGURE 8

VELOCITY PLOT AND TEMPERATURE DISTRIBUTION
(°C) WITHIN CASK CAVITY FOR CASE #2

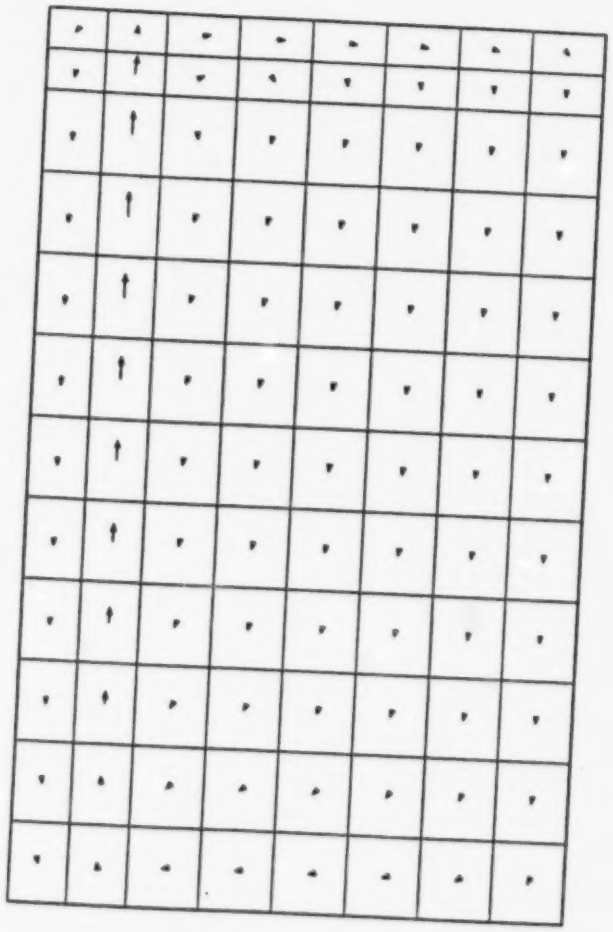
44.5	46.1	47.7	49.2	50.5	51.8	52.6	53.2	53.9	54.4	54.8	55.0	55.1	55.2
46.3	48.3	50.3	52.2	54.0	55.6	56.7	57.5	58.4	59.0	59.4	59.7	59.8	59.9
48.1	50.6	53.0	55.5	57.8	59.8	61.1	62.0	63.1	63.8	64.2	64.5	64.7	64.7
49.9	52.8	55.8	58.8	61.8	64.4	65.9	66.9	68.0	68.7	69.1	69.4	69.6	69.6
51.6	54.9	58.5	62.2	66.1	69.7	71.3	72.2	73.2	73.8	74.2	74.4	74.5	74.5
53.1	56.9	61.0	65.5	70.7	76.9	77.3	77.9	78.7	79.2	79.4	79.5	79.5	79.5
55.1	59.4	64.2	69.6	76.0	83.9								
56.5	61.2	66.4	72.3	79.0	86.9								
59.9	65.4	71.2	77.4	84.0	91.1								
61.6	67.5	73.6	79.8	86.3	93.0								
62.5	68.6	74.7	81.0	87.4	93.8								
62.9	69.1	75.3	81.6	87.9	94.3								
63.1	69.4	75.6	81.9	88.2	94.5								
63.2	69.5	75.8	82.1	88.3	94.6								
63.3	69.6	75.9	82.2	88.5	94.8								
63.5	69.8	76.1	82.4	88.7	94.9								
63.6	69.9	76.3	82.7	89.1	95.4								
63.6	69.9	76.4	83.1	90.2	98.3	106.4	110.7	114.4	116.9	118.5	119.6	120.2	120.4
63.5	69.8	76.2	82.8	89.5	96.4	102.0	106.2	110.5	113.6	115.7	117.1	117.9	118.1
63.4	69.6	75.9	82.3	88.5	94.6	99.3	103.2	107.7	111.0	113.4	115.0	116.0	116.3
63.2	69.5	75.7	81.8	87.7	93.4	97.6	101.3	105.8	109.3	111.8	113.6	114.6	114.9
63.1	69.3	75.4	81.4	87.2	92.6	96.7	100.2	104.7	108.2	110.8	112.7	113.7	114.1
63.1	69.3	75.4	81.3	87.0	92.4	96.4	99.9	104.3	107.8	110.5	112.3	113.4	113.8

Ambient Temperature = 38°C

Decay Heat = 12 W/Bundle

FIGURE 9

TEMPERATURE DISTRIBUTION (°C)
ACROSS CASK WALL FOR CASE #3



Ambient Temperature = 38°C

Decay Heat = 12 W/Bundle

87.	105.	106.	104.	98.	93.	88.	82.
89.	109.	108.	106.	100.	95.	89.	83.
91.	112.	109.	107.	102.	96.	91.	88.
91.	112.	109.	108.	104.	99.	94.	90.
91.	113.	110.	110.	106.	102.	97.	93.
92.	113.	112.	113.	109.	105.	101.	98.
92.	113.	113.	116.	113.	109.	105.	102.
93.	113.	115.	119.	117.	113.	109.	107.
93.	113.	118.	122.	121.	117.	114.	112.
94.	114.	121.	126.	125.	122.	120.	118.
96.	114.	125.	128.	129.	127.	126.	125.
98.	113.	128.	129.	128.	128.	127.	127.

T_F = 128°C + 4°C = 132°C

FIGURE 10

VELOCITY PLOT AND TEMPERATURE DISTRIBUTION (°C)
WITHIN CASK CAVITY FOR CASE #3

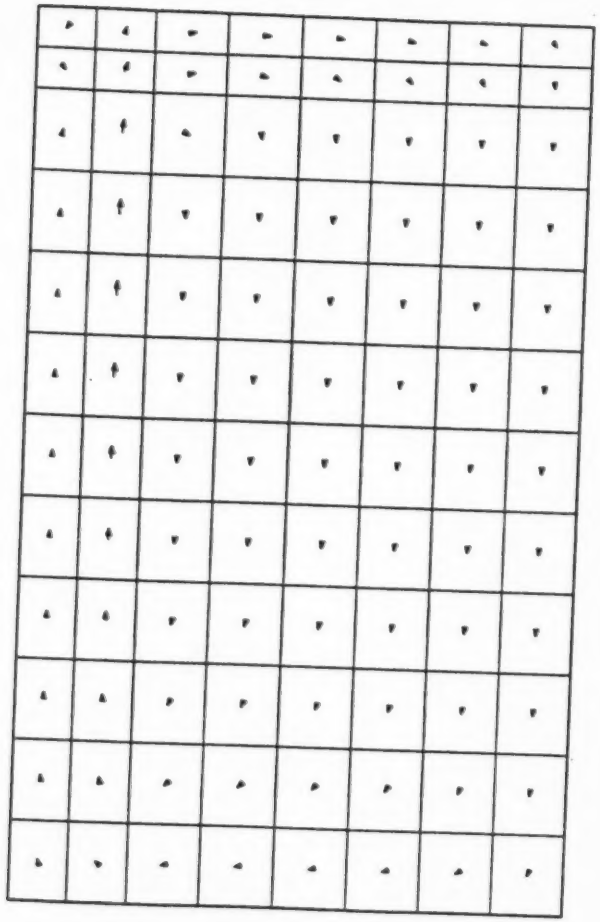
-16.9	-14.8	-12.8	-10.8	-8.9	-7.2	-6.1	-5.3	-4.4	-3.8	-3.5	-3.3	-3.1	-3.1
-14.7	-11.3	-7.8	-4.4	-1.2	1.7	3.6	5.1	6.5	7.5	8.1	8.4	8.6	8.7
-12.6	-7.8	-2.9	2.1	6.9	11.2	14.0	16.0	17.9	19.1	19.8	20.3	20.5	20.5
-10.6	-4.4	2.1	8.8	15.5	21.7	25.3	27.7	29.8	31.1	31.8	32.2	32.4	32.5
-8.7	-1.2	6.8	15.4	24.6	33.9	38.2	40.6	42.4	43.5	44.1	44.4	44.5	44.6
-7.1	1.6	10.9	21.4	33.8	50.3	53.4	54.8	55.7	56.2	56.5	56.6	56.7	56.7
-5.2	4.8	15.6	27.6	41.6	58.4								
-4.0	6.8	18.3	30.9	44.9	60.5								
-2.0	10.1	22.5	35.4	48.7	62.4								
-1.2	11.3	24.0	36.8	49.8	63.0								
-1.0	11.8	24.5	37.4	50.2	63.1								
-0.9	11.9	24.7	37.5	50.4	63.2								
-0.8	12.0	24.8	37.6	50.4	63.3								
-0.8	12.0	24.8	37.6	50.4	63.3								
-0.9	11.9	24.6	37.5	50.3	63.2								
-1.1	11.5	24.3	37.1	50.0	63.1								
-1.6	10.7	23.2	36.0	49.1	62.7								
-2.7	8.8	20.5	32.6	45.7	61.1	71.7	75.2	77.4	78.7	79.4	79.9	80.2	80.3
-3.0	8.3	19.6	31.1	42.8	54.5	62.4	67.3	71.7	74.4	76.1	77.2	77.8	78.0
-3.4	7.7	18.6	29.5	40.0	49.9	56.8	61.9	67.2	70.9	73.3	74.9	75.8	76.1
-3.6	7.1	17.8	28.1	37.9	46.9	53.3	58.4	64.1	68.3	71.2	73.1	74.2	74.6
-3.9	6.8	17.2	27.2	36.6	45.2	51.3	56.4	62.4	66.8	70.0	72.0	73.2	73.6
-3.9	6.6	17.0	26.9	36.2	44.6	50.7	55.8	61.8	66.3	69.5	71.7	72.9	73.3

Ambient Temperature = -20°C

Decay Heat = 12 W/Bundle

FIGURE 11

TEMPERATURE DISTRIBUTION (°C)
ACROSS CASK WALL FOR CASE #4



Ambient Temperature = -20°C

Decay Heat = 12 W/Bundle

56.	63.	64.	63.	62.	60.	59.	58.
58.	66.	67.	66.	66.	63.	61.	58.
63.	73.	70.	69.	68.	68.	64.	63.
66.	75.	70.	71.	70.	68.	66.	66.
67.	78.	70.	73.	73.	72.	71.	70.
68.	78.	71.	74.	75.	75.	74.	73.
69.	78.	71.	76.	78.	78.	77.	77.
70.	77.	72.	78.	80.	80.	80.	80.
71.	77.	74.	80.	82.	83.	83.	83.
71.	77.	76.	83.	86.	86.	86.	86.
71.	77.	79.	84.	86.	87.	87.	87.
70.	76.	78.	82.	83.	83.	83.	83.

T_F = 87°C + 4°C = 91°C

FIGURE 12

VELOCITY PLOT AND TEMPERATURE DISTRIBUTION
(°C) WITHIN CASK CAVITY FOR CASE #4

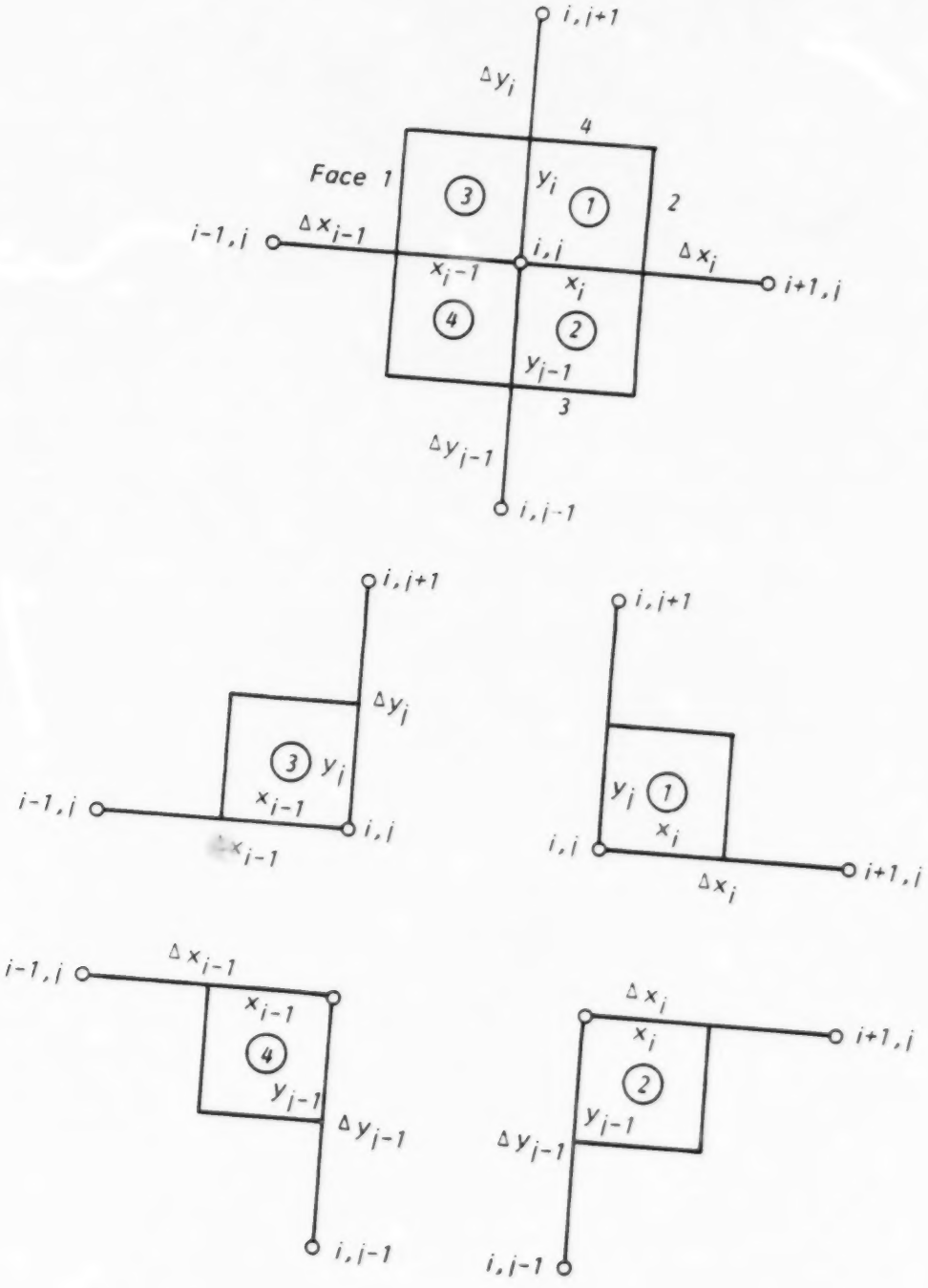


FIGURE 13
FINITE DIFFERENCE CELL FOR SOLUTION
OF HEAT CONDUCTION EQUATION

TABLE 1

THERMAL PROPERTIES

ρ (Kg/m^3)	c ($J/Kg \cdot °C$)	λ ($W/m \cdot °C$)	ν (m^2/s)	β $1/°C$
Cask Wall - Concrete *				
3500.0	838.0	2.77		
Irradiated Fuel - UO_2				
10500.0	280.0	4.0	-	-
Cavity Fluid - Air				
0.96	1009.0	0.03	2.22×10^{-5}	2.73×10^{-3}

ρ = Density

c = Specific Heat

λ = Thermal Conductivity

ν = Kinematic Viscosity

β = Coefficient of Volume Expansion

*See Reference /3/

TABLE 2
ADDITIONAL DATA

Cask Outer Surface Emissivity, $\varepsilon_E = 0.5$
Cask Inner Surface Emissivity, $\varepsilon_I = 0.7$
Fuel Region Emissivity, $\varepsilon_F = 0.7$
Fuel Region Porosity, $\phi = 0.51$

TABLE 3
CASES ANLAYZED

Case No.	Decay Heat (W/Bundle)	T_A (°C)
1	6.0	38.0
2	6.0	-20.0
3	12.0	38.0
4	12.0	-20.0

T_A = Ambient Temperature

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